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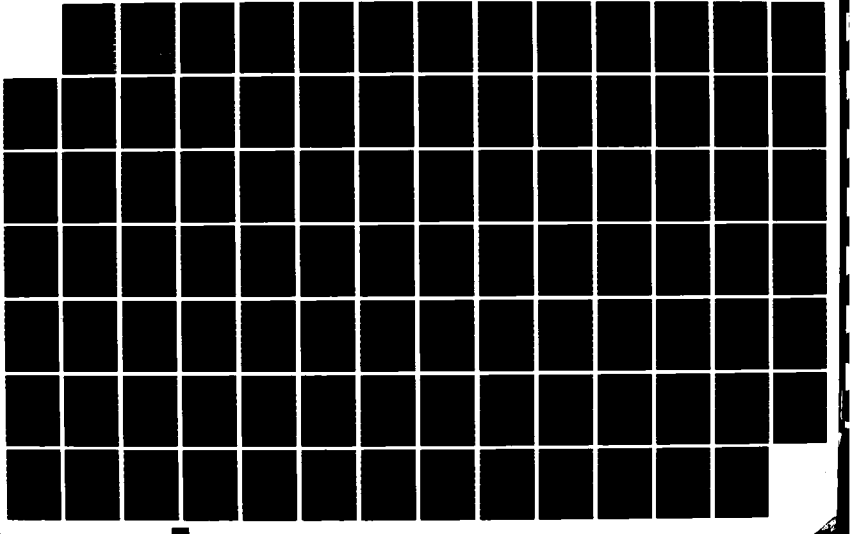

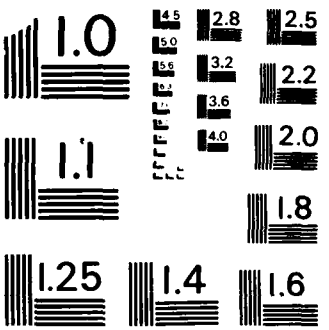

COORDINATED SCIENCE LABORATORY

PROGRESS REPORT
FOR THE
JOINT SERVICES
ELECTRONICS PROGRAM

FOR THE PERIOD
APRIL 1, 1985, THROUGH MARCH 31, 1986
FOR
CONTRACT N00014-84-C-0149

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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OFFICE OF NAVAL RESEARCH

PROGRESS REPORT

For the Period

1 April 1985 through 31 March 1986

for

Contract N00014-84-C-0149

Title of Contract
Joint Services Electronics Program

Name of Principal Investigator
Timothy N. Trick
Coordinated Science Laboratory

Name of Organization
THE BOARD OF TRUSTEES OF THE UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
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WORK UNIT NUMBER 1

TITLE: Molecular Beam Epitaxy

SENIOR PRINCIPAL INVESTIGATORS:

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M.V. Klein, Research Professor
A.Y. Cho, Research Adjunct Professor

SCIENTIFIC PERSONNEL AND TITLES:

D. Levi, Research Assistant
C.K. Peng, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this work is to use mostly optical techniques to study quantum tunneling structures, quantum wells, semiconductor superlattices and alloys grown by MBE (and occasionally other techniques such as multitarget r.f. sputtering). Of primary interest is the effect of superlattice layering and alloy disorder on the phonon Raman and infrared spectra. Also of interest is the time-dependence of phonon and electronic Raman spectra of quantum wells following excitation with a picosecond laser pulse.

SUMMARY OF RESEARCH:

During this period we have undertaken a serious effort to determine the absolute values of the optical absorption coefficient in multiple quantum wells and its dependence on the well size (in coupled and uncoupled wells). In addition, the exciton oscillator strengths were measured and compared to calculations resulting in a good agreement. The calculated absorption coefficient and transition energies also agreed with the experiment rather well [1]. Similar structures were also studied by direct reflectance measurements at 2 K where the excitonic transitions are so strong that modulation is not necessary [14]. Transitions associated with light hole and heavy hole excitons were resolved very clearly and, thus, well size fluctuations were studied in more detail. The half width of many of the transitions observed is as low as 50 μeV, which is a clear indication of the quality of the films. In some samples the exciton peaks contain very rich spectra, some of which are attributed to the fluctuations in the well size by one and two monolayer. Since these fine peaks are clearly observable, this technique can be used to determine well size and barrier uniformity across the wafer.

In a separate investigation, single quantum wells of varying sizes were grown and studied [2]. The binding energies of acceptors were also determined. More research is being carried out presently in this particular area. We have already obtained as many as 5 peaks in 25 Å single quantum wells and are in the process of identifying them.

As part of the overall program in GaAs/AlGaAs structures, we have also studied Si segregation and incorporation in AlGaAs layers with varying mole fractions and growth conditions. Silicon was found to segregate to the surface in AlGaAs, particularly if grown at high temperatures, while the GaAs did not show any noticeable segregation. The interesting result is that Si evaporates from the surface if the growth is done at 700°C coupled with increased compensation ratio.

We have performed a Raman study on optical phonons in $GaAs_xSb_{1-x}$ alloys grown by multi-target sputtering [17]. Contrary to previous reports, the Raman spectra exhibit two-mode behavior throughout the entire composition range from $0<x<1$. Broadening of the two longitudinal optic (LO) phonon peaks is less severe and less asymmetric than seen in systems such as $Al_xGa_{1-x}As$. Zone-center Raman selection rules are observed, suggesting that the spectrum involves the zero-wave-vector projection of the optical phonon density of states.

We have begun a resonance-Raman study of LO phonons in $Al_xGa_{1-x}As$ alloys grown by MBE on <100> oriented GaAs substrates [16]. Use of various combinations of photon polarization directions allowed a separation of the so-called "allowed" scattering due to electro-optic and deformation-potential electron-phonon coupling from the so-called "forbidden" scattering due to the Fröhlich mechanism. We have found an unexpected shift of $1-3cm^{-1}$ between the LO phonon seen in forbidden and allowed geometries, and this is for both the GaAs-like and the AlAs-like phonons of the alloy. This shift depends on the laser wavelength and probably represents a new manifestation of the Fröhlich interaction in alloys.

In our previous work on Raman scattering from folded acoustic phonons in GaAs/GaAlAs superlattices [3,42], we found that the phonon dispersion curve is reasonably accurately obtained by simply folding that of the virtual crystal. This leads to doublets associated with superlattice wave-vectors $2\pi m/d$, where d is the period. In a simplified model, the strength of the mth doublet is related to the mth Fourier component of the photoelastic coefficient, which in a naive model should be proportional to the mth Fourier component of the composition profile. We have tested this prediction by annealing a GaAs/AlAs binary superlattice and comparing the intensities of the doublets with x-ray intensities due to the compositional profiles [15]. The model works well for m=1, somewhat for m=3, and poorly for m=2. We have also examined the LO modes in the annealed samples to test the idea that the modes can be described using a phonon "effective mass" theory and the concept of confinement [42]. Preliminary results show reasonable agreement.

Our time-resolved Raman work on multiple quantum wells (MQWs) has been applied to pumping carriers directly into confined states of the wells [43]. We monitor the relative population of the two lowest levels at various time delays. For 220 Å wells we find that intersubband relaxation times are of the order of a 100 ps, whereas carrier cooling times are of the order of tens of ps.

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WORK UNIT NUMBER 3

TITLE: Heterostructure Electronic Devices by Metalorganic Chemical Vapor Deposition

SENIOR PRINCIPAL INVESTIGATOR:

J. J. Coleman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. A. Emanuel, Research Assistant
T. K. Higman, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this program is to extend to electronic devices the enormous impact that metalorganic chemical vapor deposition (MOCVD), as a sophisticated epitaxial growth method, has had on optical device research. This involves fundamental studies of the MOCVD growth process itself for electronic materials, studies of the electronic properties of heterostructure electronic materials and interfaces, and studies of devices made from these materials. Three specific areas of interest for this research unit are: (1) development of new reaction chamber designs and growth regimes specifically for MOCVD-grown heterostructure electronic materials, (2) structural and materials analysis, including deep-level transient spectroscopy (DLTS) and Shubnikov-de Haas measurements of quantum well heterostructure and superlattice structures, and (3) development of MOCVD-grown electronic devices, such as real space transferred electron devices and high electron mobility transistors.

SUMMARY OF RESEARCH:

A theoretical analysis of the transient response of high electron mobility transistors (HEMT) using Monte Carlo descriptions of the electron distribution has been completed. Switching times as short as 4-6 psec are predicted by the model for conventional 1 μm gate (3 μm source-to-drain spacing) devices. Conventional four-layer HEMT structures (undoped GaAs layer, undoped AlGaAs spacer layer, doped AlGaAs layer, and GaAs cap layer) have been grown by MOCVD. Although the structures are limited by the background mobility of the undoped GaAs transport layer, which is in turn limited by available metal alkyl and hydride source materials, respectable transconductances have been obtained. More complicated structures designed to exploit the advantages of the MOCVD growth process have been grown. Devices have been fabricated from structures having superlattice buffers, for example, and have shown improved saturation behavior. The alloyed metal contact and photolithographic processing technology for 1 μm gate and 3 μm source-to-drain spacing using optical lithography has been developed. First attempts have been made at sub-micron gate length processing using direct-write electron beam lithography.

Experimental studies of three-terminal real space transferred (RST) electron devices have begun. The structure of interest consists of a heavily doped, n-type conducting GaAs collector layer separated from a thin (2000 Å), lightly doped GaAs surface layer by a nearly insulating or p-type AlGaAs wide-gap barrier layer. Source and drain contacts are provided on the surface layer and a dc bias is applied to the collector. As the drain-source voltage increases, the current also increases resistively until the associated electric field becomes high enough to heat the electrons in the channel. When the field is sufficiently large that electron transfer across the AlGaAs barrier

layer becomes efficient, there is a sudden, large drop in source-drain current and a corresponding negative differential resistance. Peak-to-valley ratios in the current-voltage characteristics greater than 2:1 at 300°K and greater than 100:1 at 77°K have been observed in our first attempts at fabricating these devices. The device is especially sensitive to contact formation so shallow alloyed Au-Ge-Ag contacts have been developed for these devices and studied in detail with secondary ion mass spectrometry and high-resolution transmission electron microscopy.

A method for studying the nature of traps in heterostructures has been developed. This method, hot electron deep-level transient spectroscopy, makes use of a high electric field to heat electrons in a GaAs layer such that they undergo real space transfer into a wider-gap AlGaAs layer where they can be trapped. The field is then switched off and the trapped carriers are emitted into the AlGaAs layer and subsequently transfer back into the GaAs layer. Characteristic time constants for emission from the trap can be determined from the transient capacitance response. The method has proved to be accurate and sensitive for measurement of deep trap levels in AlGaAs and is not limited by diffusion effects, thermionic emission effects, or the rate of transfer of free electrons back to the GaAs layer.

PUBLICATIONS

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WORK UNIT NUMBER 4

TITLE: Studies of Transport Phenomena in Semiconductors

SENIOR PRINCIPAL INVESTIGATORS:

K. Hess, Research Professor
J. P. Leburton, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

D. Bailey, Research Assistant
I. Kizilyalli, Research Assistant
S. Manion, Research Assistant
T. Wang, Research Assistant

SCIENTIFIC OBJECTIVE:

This research involves the study of basic properties of semiconductors, semiconductor-heterolayers, new device concepts and device simulation. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance, especially in connection with modulation doping. The experimental studies concern mainly electronic transport in heterolayers in high electric and high magnetic fields. The theoretical studies include Monte Carlo simulations of electronic transport and the development of two-dimensional device models.

SUMMARY OF RESEARCH:

Electronic Transport at High Energies and Transient Phenomena

We have examined the role of transversal electric (gate) fields in problems of nonlinear transport [2]. It is clear that such fields by themselves do not cause any heating of the electron gas since no net current flows parallel to the field direction. Therefore, it has been customary to assume that changes due to these fields are due to size quantization. In problems of nonlinear transport, however, there are also significant classical consequences for carrier heating. The nonlinearity of high field transport is essential for these effects to occur, and the nonlinearity is strongest at very high electric fields. The influence of the transverse fields can be seen for any part of the energy distribution of electrons. However, the effect manifests itself most clearly for the high energy tail and can be explained as follows.

Under the action of an applied electric field, the electrons move through the bulk semiconductor material until quasi-steady state is established: the average energy gained from the field is balanced by energy lost to the lattice via phonon scatterings. If a potential step is introduced, as in the calculations for the square well potential, the carriers move parallel to the potential interface until scatterings redirect their momentum toward the interface. Provided the electrons have sufficient kinetic energy, gained from the longitudinal field, they can then undergo real space transfer into the high potential region [2]. Upon transferring, the electrons lose kinetic energy to the potential offset. All other factors being equal, the longitudinal field will reheat the electrons in the high potential region up to an average energy which is equal to the average in the low potential region but now measured from the minimum potential energy in the high potential region. In other

words, the electrons are heated to a maximum average energy of the usual average energy plus the potential step. We have demonstrated the importance of this effect for impact ionization and mobility degradation in field effect devices [2]. We have also continued to investigate impact ionization in bulk semiconductors and have demonstrated that the ionization role in Silicon is isotropic [1].

Electronic Transport in Semiconductor Heterolayer Structures

Several Monte Carlo simulation codes for the high electron mobility transistor (HEMT) have been developed, and a simplified ensemble Monte Carlo simulation has been completed [10]. This program is complementary to our simulation which uses only the movements of the Boltzmann Equation. It is more exact for regions of large gradients in the electric field and gives a more precise account for overshoot phenomena [10].

A second project has been an in-depth study of the "Hickmott experiment" [6,7], which shows that oscillations appear in the I-V characteristics of GaAs-AlGaAs tunnel junctions in the presence of high magnetic fields. New experimental evidence shows oscillations even at zero magnetic fields, and many interpretations have been proposed to explain this effect. We have demonstrated with a Monte Carlo simulation that some basic assumptions of several models given by other groups are invalid. These models postulate a coherence of the carrier velocity during the relaxation process by L. O. phonon emission in the buffer layer. We have generalized our previous model which is based on a mechanism of charge generation via donor ionization by L. O. phonons in the buffer layer and included the complementary mechanism of L. O. phonon resonant capture of carriers by ionized impurities. Our results are in agreement with the experimental data with and without magnetic fields and provide a general basis for the understanding of similar effects which have been encountered in tunnel junctions over the past 20 years.

Finally, a basic theory of a new type of avalanche photodiode, the complete solid state analogy to photo multiplier, has been developed. In this device, heavily doped quantum wells (the analogy of the multiplier electrodes) are sandwiched between not intentionally doped AlGaAs layers. The electrons are accelerated in the AlGaAs by intermediate electric fields and ionize electrons out of the quantum wells over the band edge discontinuity (not over the band gap). Our theory [12] is presently compared with recent experimental results by Capasso which seem to confirm the basic notion.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

The most significant accomplishment of the research described in the previous sections is, in our opinion, the theory of avalanche multiplication over the band edge discontinuity which may lead to the fabrication of a new type of avalanche photo diode. Further milestones in our research are the completion of a simulation for the Hickmott experiment and the first Monte Carlo code for the high electron mobility transistor.

INTERACTIONS AND/OR TECHNOLOGY TRANSFER:

Some of the simulation codes for transient transport have been developed in cooperation with the U. S. Army Electronics Technology and Device Laboratory, Ft. Monmouth. Interactions on heterolayer transport have continued with several groups in the Electronics Technology Division of the Naval Research Laboratory. We have transferred some of our HEMT-codes to groups at Texas Instruments, Dallas, Hewlett Packard, Palo Alto and IBM, Fishkill.

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WORK UNIT NUMBER 5A

TITLE: Crystal Growth of Semiconductor Alloys from the Vapor Phase and Controlled Doping: Ion/Surface Interactions

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SCIENTIFIC OBJECTIVE:

The primary objective of this research program is to investigate energetic particle-surface interactions which control the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconductors during vapor phase crystal growth by UHV ion beam sputtering and accelerated-beam molecular beam epitaxy. In both of these growth techniques, low energy ion-surface interactions allow an efficient coupling of kinetic energy to the growth surface upon condensation, thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing single crystal film growth at lower temperatures, much more precise control over dopant incorporation probabilities and depth distributions, and the growth of unique metastable alloys. This work is being pursued from both an analytical and an experimental point of view in order to establish a detailed understanding of the fundamental film growth mechanisms.

SUMMARY OF RESEARCH:

Surface Reaction Mechanisms, Elemental Incorporation Probabilities, and Depth Distributions of Dopants in Semiconductor Films Grown from the Vapor Phase

We have developed a general time-dependent model, which combines thermodynamic and kinetic elements, for describing the incorporation of dopants into films during deposition. The present model accounts for dopant surface segregation during the growth of single crystal films and allows elemental incorporation probabilities σ and depth dependent profiles $C(x,t)$ to be calculated for thermal dopants as a function of experimental parameters such as film and dopant material, deposition rate, incident dopant flux, film growth temperature, etc.

Input data to the model include thermodynamic parameters such as the Gibbs free energy of segregation ΔG and dopant surface binding energies E_b together with kinetic parameters such as incident fluxes and dopant diffusivities. Predictions from the present model are in excellent agreement with all known published experimental data for both acceptor and donor dopants in MBE Si and GaAs. "Anomalies" in previously published data can now be explained as being due to variations in desorption and/or surface segregation kinetics which occur in response to changes in growth temperature T_s and dopant surface coverage θ. We have calculated profiles resulting from arbitrarily complex doping schedules and have obtained excellent agreement with experimental results for Al, Ga, In, and Sb in Si, Si and Sn in GaAs, and Si in $Ga_{1-x}Al_xAs$.

Our group has carried out experiments in both MBE Si and GaAs to test theoretical predictions. Sb and In were used as model dopants in Si, while Si and Sn were investigated in the GaAs (and $Ga_{1-x}Al_xAs$) experiments. A few results are briefly summarized below.

* We predicted for the first time that there should be a critical temperature corresponding to the transition from "equilibrium" segregation of dopants to kinetically-limited segregation and used this idea in successfully fitting published data for $\sigma(T_s)$ and the profile broadening $\Delta(x,T_s)$. Furthermore, we showed in our calculations that this transition can strongly affect both σ vs T_s and profile broadening as a function of T_s since the segregation ratio r (the surface to bulk dopant fraction) has the opposite dependence on T_s in the two regimes. All of these predictions were directly verified in experiments carried out with In in MBE Si.
* We predicted for the first time that because of the high segregation ratios of many dopants in MBE Si and GaAs, surface structural phase transitions may occur during deposition due to the formation of ordered dopant overlayers. This has been verified experimentally using a combination of in-situ RHEED, LEED, and AES. We have determined the entire surface phase diagram for In on Si as a function of temperature and In coverage.
* We have calculated $\sigma(T_s)$ and $\Delta(x,T_s)$ for important molecular doping species such as Sb_4 in Si where a knowledge of the details of complex surface reaction paths are required. Modulated-beam mass spectrometry (MBMS) and thermally stimulated desorption (TSD) measurements were used to determine: the sticking probability of Sb_4 on Si(100) and the desorption rates of Sb_n ($n = 1,4$) as a function of T_s and θ; the saturation coverage and the surface lifetime of Sb as a function of T_s; and the activation energy for Sb_1 desorption (Sb_4 was dissociatively chemisorbed on clean Si(100) at all temperatures investigated, 100-1025 °C). E_{Sb} was found to decrease from 2.40 eV at $\theta < 0.5$ ML to 2.33 eV at higher coverages due to a surface phase transition. A simple model for Sb_4/Si(100) interactions involving a mobile Sb_4 precursor state and repulsive lateral interactions between chemisorbed Sb adatoms was used to calculate desorption rate kinetics and was found to provide excellent agreement with the measured data.
* $\sigma(T_s)$ and $\Delta(x,T_s)$ were measured for In in MBE Si, Si in MBE GaAs, Si in MBE $Ga_{1-x}Al_xAs$, and S in sputter-deposited GaAs. Values of ΔG and E_b were then obtained by fitting the results using the dopant incorporation model.
* The model has been used in "reverse" to predict growth parameters for obtaining better control over dopant depth distributions, particularly in modulation-doped layers. Experimental results, especially those involving accelerated-beam doping, have shown good success.

Ion/Surface Interactions During Crystal Growth

Low-energy ion bombardment of the film *during* deposition provides an efficient coupling of kinetic energy to the growth surface thereby altering the surface reactivity as well as adsorption, adatom diffusion, nucleation kinetics, and growth kinetics. This is turn can lead to epitaxial growth at lower temperatures, much more control over dopant incorporation probabilities and depth distributions, and the growth of unique metatable alloys. All of these effects have been demonstrated by laboratories across the world using a variety of techniques including accelerated-beam MBE, sputter deposition, and PA-CVD. Our group has begun to model ion/surface

interaction effects which are common to all of these growth techniques and to design and carry out some of the first definitive experiments under well-controlled conditions to probe fundamental interaction mechanisms. Some of the highlights of this work are briefly summarized below.

* We have added additional terms to the dopant incorporation model discussed above which account for trapping (low energy implantation) and enhanced diffusion. These terms affect both the steady state value as well as the time evolution of the dopant surface coverage θ and the segregation ratio r. Thus, accelerated-beam doping will alter the dopant incorporation probability σ not just by implantation but also through changes in segregation kinetics, desorption rates, and, in the case of plasma-based techniques for which the ion current can be large compared to the thermal flux, sputtering rates from the growing film. Thus, accelerated doping can also be expected to have a significant affect on doping profiles in the growing film.

* We have carried out initial experiments using In^+ doping during MBE Si and Zn^+ doping during MBE GaAs and measured increases in σ of up to 5 orders of magnitude in the former case and over 10 orders of magnitude in the latter using ion acceleration energies as low as 20 eV. In addition, the segregation-induced broadening, which we have shown can be severe in In-doped Si, was greatly reduced.

* The first definitive experiments designed to investigate the role of ion-energy ion irradiation *during* film growth have been initiated using In on Si as a model system. We have studied the nucleation and growth kinetics of thermal In on clean Si(100)2x1 surfaces in detail using RHEED, LEED, AES, TSD, and SEM in order to establish a reference for accelerated-beam growth studies. The surface phase diagram for In on Si(100) was determined. At all temperatures investigated, 30 to 650°C (note that In melts at 156°C), In was found to initially nucleate and grow two-dimensionally in a Stranski-Krastanov mode while classical theories would predict three-dimensional growth for a relatively noninteracting system such as In/Si.

  We have shown that In growth kinetics and resulting island morphologies in thick overlayers grown at $T_s < 150$°C are completely different for films grown on Si(100)2x1 and Si(100)3x4 surfaces (the latter was obtained by depositing $\sim$ 1 ML of In on Si(100)2x1 at $T_s > 150$°C and then cooling below 150°C). This has important consequences for the control of film microstructure. We have also found that the use of low-energy accelerated In^+ beams dramatically affects film nucleation and growth kinetics. The experiments were carried out in the same MBE chamber on both Si(100)2x1 and Si_3N_4 substrates. TEM studies of films grown on Si_3N_4 showed that ion irradiation greatly increased the nucleation and adatom surface diffusion rates giving rise to a much more oriented growth habit with larger grains. In the case of deposition on Si, we observed quite different surface structures and two-dimensional growth persisted to much higher coverages than for thermal In deposition.

Crystal Growth and Physical Properties of Single-Crystal Metastable Semiconductors

We have carried out the detailed studies of the growth and physical properties of new single crystal metastable semiconductors. The key feature in stabilizing the growth of these materials is the controlled use of low-energy ion bombardment to modify the incorporation probabilities of the matrix elements (not just the dopants as discussed above) and to promote dynamic collisional mixing during deposition. We have concentrated primarily on the study of $(GaAs)_{1-x}(Ge_2)_x$ in this research program because of the importance of the end members, the interest in Ge-GaAs heterostructures, and the fact that it is representative of a new subclass of potentially important alloys, $(III-V)_{1-x}(IV_2)_x$. In addition, we have recently grown epitaxial alloys of $(GaSb)_{1-x}(Sn_2)_x$ and $Ge_{1-x}Sn_x$ representing two other subclasses of metastable semiconductors.

* The equilibrium GaAs-Ge phase diagram has been determined by differential thermal analysis and X-ray diffraction annealing studies to be a simple eutectic with an invariant temperature and composition of 880 °C and $\sim$ 8 mole % GaAs, respectively. The maximum solid solubilities of GaAs in Ge and Ge in GaAs are $\sim$ 4 mole %.

* Epitaxial metastable $(GaAs)_{(1-x)}(Ge_2)_x$ alloys with compositions ranging from x = 0 to x = 1 have been grown on GaAs(100) and GaP(100) substrates by ion beam sputtering in ultra-high vacuum. Electron channeling, X-ray diffractometry, X-ray topography analysis, and TEM studies indicate that the films are of very high crystalline perfection.
* We have used high resolution triple crystal X-ray diffraction measurements of the (200) superstructure and (400) fundamental reflection intensities from $(GaAs)_{(1-x)}(Ge_2)_x$ films on GaP(100) substrates to provide the first direct evidence that there is in fact a long range order/disorder transition near x = 0.3.
* $(GaSb)_{(1-x)}(Sn_2)_x$ alloys with x up to 0.23 have been grown on GaAs(100) even though the equilibrium phase diagram exhibits no solid solubility. Growth phase maps and decomposition reaction paths have been determined. The $(GaSb)_{(1-x)}(Sn_2)_x$ crystalline-metastable to equilibrium phase transformation proceeds through a much different reaction path, due to structural constraints, than in $(GaAs)_{(1-x)}(Ge_2)_x$. Initial Raman results show that Sn-based $(III-V)_{(1-x)}(IV_2)_x$ alloys exhibit a "two-mode" behavior.

Related Technological Developments

* We have developed the first low-energy, ultra-high vacuum compatible, ion sources which can be operated with gas, liquid, or solid charges. The ion guns utilize single grid optics, provide relatively high current densities for acceleration energies as low as 20 eV, and have been operated for hundreds of hours with Zn, As, Sb, and In. These guns are of particular value for accelerated-beam doping during MBE and for carrying out fundamental studies of ion/surface interactions.

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WORK UNIT NUMBER 5B

TITLE: An Investigation of the Plasma and Chemistry Processes in Cylindrical Magnetron Reactive Ion Etching Discharges

SENIOR PRINCIPAL INVESTIGATOR:

J. A. Thornton, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

G. Y. Yeom, Research Assistant

SCIENTIFIC OBJECTIVE:

The primary objective of this research is to investigate fundamental plasma and chemistry processes in a type of magnetically confined discharge that has promise for reducing radiation damage during device processing by dry etching.

Objectives

This program has three objectives. One objective is to investigate the basic behavior of rf-driven magnetron plasmas and the resultant plasma surface reactions. A second objective is to explore plasma chemistry behavior in low pressure rf-driven magnetron discharges using working gases (CF_4–H_2 and CF_4–O_2) that are relevant to plasma-assisted etching. A third objective is to examine the degree to which the radiation damage produced in silicon by reaction ion etching can be reduced through the use of magnetron plasma sources.

SUMMARY OF RESEARCH:

Experimental Plan and Expected Results/Impact

The operation of rf-driven magnetrons for plasma-assisted materials processing raises three issues: (1) What electrode/wall bombardment energies can be obtained? (2) What volume chemistry can be achieved in the unique combination of high electron density and low gas density which is possible in a magnetron plasma source?, and (3) What surface chemistry can be promoted by the combination of active and energetic species that can be generated in magnetron plasma sources?

The energy of charged species passing from a plasma to electrode or wall surfaces depends on the instantaneous difference between the plasma potential and the potential of the surface in question. The variation in plasma potential with position and time depends on the discharge physics and is only recently becoming understood for the conventional plane-parallel electrode case [5-10], with very little work having been done on plasma magnetrons [11]. Thus, we expect our work in this area to have immediate significance to both the sputter deposition and plasma chemistry communities.

We are using two approaches to determine the electrode wall bombardment energies. In the first approach we are making spatial and temporal measurements of the floating potential within the magnetron plasma, using electrostatic probes. Plasma potentials will be deduced from these floating potential measurements by making complete probe characteristic measurements at selected positions. In the second approach, multi-grid electrostatic analyzers located at the electrode wall surfaces will be used to measure the energy of incident ions.

The volume chemistry within the magnetron plasma depends on the electron density and the electron energy distribution function. The many possible reaction paths in molecular etching and deposition plasmas, and the difficulty in measuring the electron distribution function, have delayed progress in this area [12]. Virtually no work has been reported on the chemistry in magnetron discharges. Our experiments are designed to use optical emission spectroscopy and mass spectroscopy to examine the chemistry in the magnetron discharges.

The electron distribution function will be investigated by seeding the plasma with small amounts (1 to 5%) of inert gases having line radiation excitation thresholds covering a range of electron energies. Typical excitation energies are Xe (11 eV), Ar (13.5 eV), Ne (18.7 eV) and Ne (21.1 eV). Under the conditions of interest in the magnetron plasma, the line radiation results from atoms which are excited from the ground state by electron impact mechanisms that are very similar to those that produce molecular dissociation and therefore the radicals that serve as precursors to the plasma chemistry. The rates of excitation, and therefore the line intensities, depend on the integral of the electron distribution function over the energy range exceeding the threshold. Ratios of line intensities remove the dependence on electron density. Therefore collectively the line radiation data provide information concerning the electron distribution function over the high energy tail region that is particularly relevant to the plasma chemistry. Accordingly, observations of line intensity ratios, as the magnetron operating conditions are varied, will be used to provide a measure of variations in the important high energy tail region of the electron distribution function.

The reaction paths within the CF_4–H_2 and CF_4–O_2 working gases that are being used as study vehicles can be divided into four channels: (1) electron impact, (2) molecule-molecule, (3) hydrogen abstraction, and (4) florine abstraction. Preliminary computer modeling calculations indicate that the wide working gas pressure range that is available in the megnetron sources should permit considerable control in promoting various reaction channels. Spectral line ratio measurements will permit determination of the relative concentrations of species such as F, H, O, CO and CF_2 that are identifiable products of the various channels. These measurements will be supplemented by modulated beam mass spectroscopy measurements which will be made to identify radical species reaching the chamber wall. Laser-induced fluorescence may also be used in the future to supplement the optical plasma-induced emission studies.

The final aspect of the present investigation involves the actual reactive ion etching process and damage that is induced in silicon. The work is planned to proceed at two levels. In work presently under way, the etching effectiveness of the species generated in CF_4–H_2 and CF_4–O_2 magnetron plasmas will be investigated by observing the relative etch rates of SiO_2 and Si. Thus, particular attention will be given to determining the relationship among the volume chemistry, the SiO_2/Si selectivity, and the ability to etch step side walls. The damage induced in Si by the reactive ion etching will be examined by fabricating MOS capacitors on the etched material and making capacitance-voltage measurements. Although studies of reactive ion etching with magnetron sources have been reported for Si [13], and more recently GaAs [14], systematic studies of concurrent damage have not.

A fundamental understanding of the detailed surface chemistry that characterizes the reactive ion etching process in general, and the magnetron RIE case in particular, can be obtained only by modulated beam type studies that are conducted in ultra-high vacuum systems configured to isolate certain reactions and to permit *in situ* surface measurements [3]. The difficulty with these studies is that they are very time consuming, so that the range of effective operating conditions that can be covered is limited. Therefore, they must be preceded by more macroscopic studies which define to a greater degree of the atomic level conditions of particular interest. At least for the case of etching at the wall electrode of the cylindrical magnetron system, the mass spectroscopy measurements of the incident ion and radical species, and the electrostatic measurements of the ion energies, are designed to provide the information that would be required to design suitable modulated beam studies using remote plasma sources.

Accomplishments

An experimental magnetron discharge apparatus with provisions for making various measurements within the plasma and at the plasma-wall interfaces has been designed and constructed. It consists of a cylindrical stainless steel vacuum chamber, 20 cm in diameter by 30 cm high, which is configured to accept axially mounted flange-type [15] cylindrical magnetron electrodes having diameters of 1.5 cm, 2.5 cm, and 10 cm. These electrodes will permit rf discharge experiments with electrode area ratios, between the driven magnetron electrode and the grounded chamber, ranging from about 50 down to about 5. Rf power supplies are available for driving the discharge at frequencies of 1.8 MHz and 13.56 MHz. External magnetic field coils are configured in a special arrangement that was developed to provide the required uniform magnetic field within the chamber (about 200G), while leaving the sides of the chamber wall accessible for instrumentation [2]. The field strength is uniform within about 10% over the primary region of the chamber volume that is occupied by the magnetron plasma.

Ports are available on the chamber wall for making optical emission spectroscopy measurements and for introducing electrostatic probes that can provide measurements in both the radial and axial directions across the magnetron discharge. A retarding grid electrostatic analyzer is mounted on the chamber wall to permit measurements of the energies of plasma species incident on the grounded electrode and therefore, along with the electrostatic probe measurements, to obtain information concerning the plasma potential. It is anticipated that as the work proceeds, an electrostatic analyzer will also be installed within the 10 cm diameter cylindrical electrode so that the energy of plasma species incident on the powered electrode can also be measured. Another port on the chamber wall is configured to mount a modulated beam mass spectrometer which can be used to measure the identity of chemical species which pass from the magnetron plasma to the chamber wall surface. A spectrometer system, which is being developed on another program, will be available for part-time use on the JSEP program. Species incident on the chamber wall pass into the mass spectrometer through a small orifice and are formed into a molecular beam by a second orifice arranged between two stages of pumping. The molecular beam is mechanically chopped to facilitate phase lock-in detection and then passed into the ionization section of a Balzers type ZMA 140 quadruple mass spectrometer. A perpendicular mounting configuration of the mass filter is used to eliminate spurious signals due to secondary species released from energetic particle bombardment within the spectrometer. The spectrometer can also be mounted in the axial configuration, which includes suitable optics for direct ion detection.

Primary experiments have been conducted in which the system has been operated at direct currents and at 1.8 MHz using He and Ar as working gas. Rf experiments during the next two months with He and Ar will investigate the effect of the electrode area ratio on the plasma potential distribution and the ion bombarding energies. Experiments with CF_4–H_2 and CF_4–O_2 will then be initiated.

Preliminary computer calculations have been made to model the chemistry in a $CF_4 - H_2$ plasma. The objective was to examine the influence of the combination of high electron densities and low gas densities, which can be obtained in magnetron plasmas, on the resulting chemistry. The calculations were made for plasma conditions that span from those used in conventional planar diode reactive ion etching reactors to those that are accessible with the cylindrical magnetrons. Thus, gas densities were varied from $10^{13}cm^{-3}$ to $10^{15}cm^{-3}$, and electron densities from $10^{9}cm^{-3}$ to $10^{11}cm^{-3}$, with an effective electron temperature of 3 eV. Cross sections were taken primarily from references 16 and 17. The calculations confirm that magnetron discharges operating under typical low gas pressure (density $\sim 10^{13}\ cm^{-3}$) - high electron density conditions will provide the same electron impact dissociation rates as are obtained in conventional discharges (i.e., gas density x electron density product is the same). However, molecule-molecule reactions, which involve the interaction of plasma-produced radicals with the CF_4 working gas and produce larger molecules which can serve as the precursors to polymer formation, are reduced in the low pressure magnetron case.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] J.A. Thornton, "Gas discharge processes for thin film deposition," invited paper presented at Sixth Inter. Conf. on Thin Films, Stockholm, Sweden, August 13-17, 1984. (JSEP)

[2] A.S. Penfold, G. Yeom, and J.A. Thornton, "An effective magnetic field configuration for cylindrical magnetrons," in preparation. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[3] H.F. Winters, R.P.H. Chang, C.J. Mogab, J. Evans, J.A. Thornton, and H. Yasuda, "Coatings and surface modification using low pressure non-equilibrium plasmas," *Materials Science and Eng.*, vol. 70, pp. 53-77, 1985. (DOE)

[4] J.A. Thornton, "Microstructure considerations in hydrogenated amorphous silicon thin films," to be published in *Acta Met* (1986). (EPRI)

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[8] M. Kushner, "Distribution of ion energies incident on electrodes in capacitively coupled rf discharges" *J. Appl. Phys.*, vol. 58, p. 4024, 1985.

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[11] I. Lin, "Steady-state rf magnetron discharges," *J. Appl. Phys.*, vol. 58, p. 2981, 1985.

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[17] D. Edelson and D.L. Flamm, "Computer simulation of a CF_4 plasma etching silicon," *J. Appl. Phys.*, vol. 56, p. 1522, 1984.

WORK UNIT NUMBER 6

TITLE: Acoustic Charge Transport

SENIOR PRINCIPAL INVESTIGATORS:

B. J. Hunsinger, Research Professor
M.J. Hoskins, Visiting Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

E. Bogus, Research Assistant
J. Dallesasse, Research Assistant
F. Fliegel, Research Assistant
W. Hunt, Research Assistant
D. Janes, Research Assistant
R. Miller, Research Assistant
J. Peterson, Research Assistant
G. Pieters, Research Assistant
J. Pryst, Research Assistant
R. Rhoades, Research Assistant
B. Schmukler, Research Assistant
C. Warren, Research Assistant

SCIENTIFIC OBJECTIVES:

The Acoustic Charge Transport (ACT) device is a new type of signal processing device which provides high-speed charge transfer and charge-sensing operations in GaAs. Electron transport is accomplished in a buried channel GaAs structure using the traveling wave electric field of a Surface Acoustic Wave (SAW) generated directly in the GaAs. After injection into the ACT device, signal charge may be processed by nondestructive sense electrodes located along the transport channel to realize general transversal filter functions.

The large bandwidth and low noise properties of ACT devices make them suitable for a wide range of applications in large time-bandwidth product signal processing. The integration of ACT devices with other microwave components in GaAs holds the promise of achieving very powerful monolithic signal processors because the conventional GaAs I.C. technology can provide gain and control while the ACT device provides the compact, low power, fast memory required for real time computations.

Studies of ACT device physics and modeling, GaAs SAW technology, and GaAs fabrication technology represent the primary objectives of this research area.

SUMMARY OF RESEARCH:

ACT Device Physics and Modeling

Traveling Wave Charge Injection. The complicated theoretical problem of charge injection into an ACT device is addressed. The problem is analyzed with a computer model which was developed for simulating the injection process. The model, which includes the effects of material parameters, bias structures, and acoustic amplitude, provides a means of obtaining theoretical predictions and performance trends for injection parameters. Results of the simulations show good agreement with experiment.

Nondestructive Sensing. A theoretical model is formulated to describe charge detection by capacitively coupled sense electrodes on the surface of the ACT device. The comprehensive small signal theory provides the frequency response and sensitivity of nondestructive charge sensing electrodes. Excellent agreement with experiment has been obtained.

Transport Research. Various field problems are studied and analyzed to assess the impact of nonuniform surface structures and arbitrary doping profiles on charge storage, transfer inefficiency, and charge extraction in the charge transport device.

GaAs Surface Acoustic Wave Research

GaAs SAW Generation and Waveguides. A detailed theory has been developed to describe SAW generation by interdigital transducers on GaAs where the second order effects of internal reflections and resistive electrode losses are non-negligible. The theory gives guidelines for transducer design to optimize generation efficiency. SAW propagation in GaAs waveguide structures is also investigated and the application of these structures in the ACT device is explored. The guide provides an elegant means for achieving controlled propagation of high-power acoustic fields which are necessary for low transfer inefficiency.

GaAs SAW Propagation. The fundamental properties of SAW propagation and diffraction in both bare GaAs and GaAs with surface electrodes are investigated. A method for computing the slowness surface of GaAs from laser probe scans was developed. This data is then used in a standard diffraction theory analysis program to accurately predict the magnitude and phase of a propagating beam profile. Preliminary work indicates that the diffraction of a beam propagating in unmetallized GaAs does not vary with acoustic power.

GaAs Fabrication Technology

Low Process Temperature Dielectric Research. A fabrication process has been developed for defining polyimide dielectric features for GaAs I.C. applications where low process temperature schedules are required to preserve the structural and electronic quality of circuit features. The electrical characteristics of the resulting dielectric have been evaluated and have been found to give adequate DC and RF characteristics for GaAs integrated circuit and crossover applications.

Deep Implantation Research. A process for achieving a photolithographically definable high-resolution mask which is capable of withstanding high-energy particle bombardment has been developed. This basic process has served as the foundation for constructing ACT device architectures based on high-energy proton isolation. Initial studies of device isolation effectiveness have been completed.

Schottky Barrier Leakage Research. An initial investigation of the impact of diode edge guarding, barrier metal type, and process temperature on the reverse biased leakage current of Schottky barrier GaAs diodes has been performed. The work indicates that drastic reductions in leakage current may be obtained through a proper choice of barrier metal type and process temperature.

WORK UNIT NUMBER 7

TITLE: Vapor Phase Growth and Characterization of InGaAs and InGaAsP Heterostructures and Devices

SENIOR PRINCIPAL INVESTIGATOR:

G. E. Stillman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. S. Bose, Research Assistant
R. DeJule, Research Assistant
M. A. Haase, Research Assistant
M. Kim, Research Assistant
N. Pan, Research Assistant
A. Reed, Research Assistant
V. Robbins, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this research unit is to contribute to our understanding of impurity incorporation mechanisms, sources, and defects, and to improve our understanding of the influence of growth conditions on impurities and defects. It includes developing new characterization techniques that will extend the range of impurity concentrations over which quantitative analysis is possible.

SUMMARY OF RESEARCH:

The photoluminescence and photothermal ionization spectroscopic techniques for the study of impurities in GaAs have been further refined and applied to the study of the influence of growth technique, growth parameters, substrate orientation, and source materials on the incorporation of impurities in GaAs for MBE, MOCVD, and other epitaxial growth techniques.

In collaboration with J.C.M. Hwang, formerly with Bell Laboratories and now with General Electric Company, Electronics Laboratory, Syracuse, N.Y., we have characterized high purity Si-doped MBE grown GaAs using these techniques [4]. The high-purity, lightly Si-doped ($\mu 77 \approx 70000-126000 cm^2/V\,s$ and $n_{77} \approx 2-8 \times 10^{14} cm^{-3}$) molecular beam epitaxy (MBE) GaAs layers were characterized using variable-temperature Hall effect and C-V measurements, photothermal ionization spectroscopy, low-temperature photoluminescence (PL), and deep level transient spectroscopy (DLTS). The spectroscopic measurements of the residual donors and acceptors indicate that the pronounced increase in carrier concentration which is observed with increasing As flux (for a constant Ga Flux) results from incorporation of additional residual S donors which are present in the metallic As source material, and not from reductions in the Si acceptor concentration or residual C acceptor concentration. The increase in carrier concentration with As flux is considerably more pronounced when using an alternative source of As, which introduces S and 3 additional donor species. The C acceptor concentration increases with As flux using either of the metallic As sources, although the increase is much stronger with the alternative source. The dependence of C concentration on the As source implies that the As source itself contributes at least part of the C

background. The Si acceptor concentration is negligible for the range of growth conditions that were used. Close compensation between the residual S donors and C acceptors may account for the high resistivity previously observed in undoped samples grown in this system using the purer As source. The PL data exhibit very weak "defect"-related emissions in the 1.504-1.512 and 1.466-1.482 eV ranges; our measurements support the existence of a correlation between these two sets of peaks, in agreement with previous work of Briones and Colins. Temperature and excitation intensity-dependent PL measurements are used to demonstrate conclusively that the peaks in the 1.466-1.482 eV range are donor-to acceptor and band-to-acceptor in nature, involving normal shallow donors and at least four different acceptor levels whose exact origin is unknown. The "defect" peak intensity is larger in the less pure material which contains more C, implying that the "defects" may be C related. Several electron traps including M1, M3, and M4 are observed in the DLTS spectra, and the C-V measurements give a total trap concentration of $3 \times 10^{13} cm^{-3}$ [6].

The technique of photothermal ionization Fourier transform spectroscopy of shallow donors is very useful for the detection and identification of residual impurity species in high purity compound semiconductors, especially GaAs. However, the extension of this technique in less pure or intentionally doped samples has resulted many many incorrect impurity identifications. We have studied how the photothermal ionization spectra change with impurity concentration, thickness, and magnetic field, and developed a model of the dielectric response of shallow impurity states which explains many of the previously anomalous results [2].

In addition to predicting the behavior of the anomalous notched photothermal ionization peaks, the model of donor dielectric response makes some very important predictions regarding the interpretation of more conventional looking spectra. Specifically, the model demonstrates that the conventional assumption that the photoconductive response is proportional to the product of the neutral donor concentration and the probability distribution of the transition energies is not correct. This assumption is based on the incorrect idea that the total number of donors in a high purity sample is so small that the associated FIR absorptance is very small. For realistic sample parameters the absorptance can actually be close to unity. The above assumptions lead to several incorrect conclusions, many of which have been routinely used in the interpretation of photothermal ionization spectra, that are corrected with the donor dielectric response model.

Because the probability distribution of transition energies should be essentially the same for all donors within a given hydrogenic transition, the ratios of the photothermal ionization or absorption peak heights within a given transition would be expected to be equal to the ratios of concentrations of the corresponding donor species. The model of donor dielectric response shows that this conclusion is incorrect, and in fact can lead to gross errors, especially when the absorptance due to one or more of the donor species closely approach unity. This fact has important implications for the proper quantitative interpretation of such spectra in the study of impurity incorporation in high purity material.

The spectral peak shapes would also be expected to be the same as that of the corresponding transition energy probability distribution, and to all have a width equal to the inhomogeneous width. If this were so, then all peaks within a given hydrogenic transition would have the same width, and this is certainly not observed experimentally. The dielectric response model predicts that the absorptance and photothermal ionization peak shapes can be dramatically different from that of the probability distribution, and that, even in spectra containing no notched peaks, the peak widths are often substantially larger than the inhomogeneous width.

In the proposed work, high purity GaAs and InP samples grown in many different laboratories by many different techniques will be used. The sources of the samples by growth technique are listed in the following tables.

Table 1

Sources of High Purity GaAs

LPE	
J. K. Abrokwah	Honeywell Technology Center
E. Bauser	Max Plank Institute, Stuttgart
G. E. Bulman	University of Illinois
L. F. Eastman	Cornell University
P. D. Green	Standard Telecomm. Laboratories
D. E. Holms	Hughes Research Laboratories, Malibu
C. E. Stolte	Hewlett Packard Laboratories
E. Kuphal	Forschunginstitute der DBP beim FTZ F.D.R.
X. R. Xhong	Institute of Semiconductors, Bejing
$AsCl_3$ VPE	
C. O. Bosler	M.I.T. Lincoln Laboratory
T. H. Miers	Motorola Incorporated
G. L. McCoy	Wright-Patterson Air Force Base
A. Shibatomi	Fujitsu Laboratories
C. M. Wolfe	Washington University
P. Colter	University Energy Systems
X. R. Xhong	Institute of Semiconductors, Bejing
K. Arai	NEC Corporation
AsH_3 VPE	
J. K. Abrokwah	Honeywell Technology Center
J. K. Kennedy	Hanscom Air Force Base
T. J. Roth	University of Illinois
R. Sankaran	Avantek
A. Usui	NEC Research Laboratories
MOCVD	
P. D. Dapkus, K. Hess	Rockwell International
T. Nakanisi, T. Udagawa	Toshiba Corporation
R. Bhat	Bell Laboratories, Murray Hill
L. F. Eastman, J. R. Shealy	Cornell University
J. J. Coleman	University of Illinois
M. Feng	Ford Microelectronics
P. E. Norris	General Telephone & Electronics
F. T. J. Smith	Kodak Research Laboratories
K. A. Jones	University of Massachusetts, Amherst

Table 1
(Continued)

Sources of High Purity GaAs

MBE	
A. R. Calawa	M.I.T. Lincoln Laboratory
D. M. Collins	Hewlett Packard Laboratories
J. C. M. Hwang	Bell Laboratories, Murray Hill
H. Morkoc,	University of Illinois
A. Y. Cho	Bell Laboratories, Murray Hill
C. E. C. Wood, L. F. Eastman	Cornell university
S. Palmateer	General Electric, Syracuse
M. Heiblum, W. I. Wang	IBM
D. Miller	Rockwell International
E. Caine	University of California, Santa Barbara
K. Arai	NEC Corporation

Table 2

Sources of High Purity InP

LPE	
L. Cook	University of Illinois
K. W. Benz	University Stuttgart
R. Malik	Cornell University
E. Kuphal	Forschunginstitut der DBP beim FTZ F.D.R.
PCl_3-VPE	
V. G. Keramidas	Bell. Comm. Res
PH3-VPE	
T. Roth	University of Illinois
MOCVD	
K. Hess	Rockwell International
K. W. Carey	H.P.
Polycrystalline Czochralski InP	
J. K. Kennedy	Hanscom AFB
G. Iseler, A. Strauss	MIT

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] T. S. Low, M. H. Kim, B. Lee, B. J. Skromme, T. R. Lepkowski, and G. E. Stillman, "Neutron transmutation doping of high purity GaAs," *J. Electron. Mater.*, vol. 14, pp. 477-511, 1985. (AFSOR/ONR/JSEP)

[2] G. E. Stillman, T. S. Low, and B. Lee, "Photothermal ionization fourier transform spectroscopy of shallow donor states in III-V semiconductors," *Solid State Commun.*, vol. 53, pp. 1041-1047, 1985. (AFSOR/DARPA/JSEP)

[3] V. M. Robbins, T. Wang, K. F. Brennan, K. Hess, and G. E. Stillman, "Electron and hole impact ionization coefficients in (100) and in (111) Si," *J. of Appl. Phys.*, vol. 58, no. 12, pp. 4614-4617, Dec. 15, 1985. (JSEP/ONR/NSF)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[4] B. J. Skromme, S. S. Bose, B. Lee, T. S. Low, T. R. Lepkowski, R. Y. Dejule, G. E. Stillman, and J. C. M. Hwang, "Characterization of high purity Si-doped molecular beam epitaxial GaAs," *J. of Appl. Phys.*, vol. 58, pp. 4685-4702, Dec. 15, 1985.

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[8] V. M. Robbins, and K. Hess, "Impact ionization in InP and GaAs," in *Proc. Fourth Int. Conf. on Hot Electrons in Semiconductors, Physica*, vol. 134B, pp. 241-246, 1985. (ONR)

WORK UNIT NUMBER 8

TITLE: Direct Examination of the Metal-Semiconductor Interface

SENIOR PRINCIPAL INVESTIGATOR:

G. Ehrlich, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. D. Wrigley, Research Associate

SCIENTIFIC OBJECTIVE:

Silicon interfaces have, for a long time, been of paramount importance in device technology. However, the atomic events significant for the formation of metal-silicon interfaces or for their stability are not well understood. The aim of this project is twofold: (1) to examine the interactions of silicon atoms with metal surfaces, using field ion microscopic techniques to attain a direct view, on the atomic level, of the processes important in layer formation; and (2) to characterize the atomic structure of the interface. Particular emphasis will be upon the variations in behavior dictated by the structure of the substrate, as well as the effect of foreign atoms upon the properties of the layers formed.

SUMMARY OF RESEARCH:

The work in this unit has been concentrated on characterizing interactions between a single silicon atom and a metal atom at a surface, so as to provide information about the energetics of silicon-metal overlayers. During the past year, this effort under JSEP sponsorship has drawn to a close. No new scientific studies have been undertaken, and activities have been devoted entirely to terminating this project.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] J. D. Wrigley and G. Ehrlich, "Atomic interactions in silicon-metal complexes on W(110)," in *Proc. Materials Research Society Symp.*, vol. 48, Materials Research Society, pp. 47-53, 1985. (JSEP)

[2] J. D. Wrigley and G. Ehrlich, "Summary abstract: Diffusion and dissociation of silicon-metal complexes on W(110)," *J. Vac. Sci. Technol. A.*, vol. 3, no. 3, pp. 1572-1573, May-June 1985. (JSEP)

[3] J. D. Wrigley and G. Ehrlich, "Direct observation of diffusion for metal-silicon complexes on W(110)," in *Abstracts, 32nd Int. Field Emission Symp.*, Wheeling, West Virginia, July 1985. (JSEP)

[4] J. D. Wrigley and G. Ehrlich, "Atomic jump rates in hetero-clusters," *J. Vac. Sci. Technol. A* vol. 4, in press. (JSEP)

[5] F. Watanabe and G. Ehrlich, "Surface diffusivities from concentration profiles," *J. Vac. Sci. Technol. A.*, vol. 4, in press. (JSEP/NSF*)

ADDITIONAL INFORMATION:

Awards and Honors:

F. Watanabe

Best Poster Award, American Vacuum Society 32nd National Symposium, Houston, Texas, Nov. 1985

G. Ehrlich

National Academy of Sciences

*NSF funding is a Materials Research Laboratory grant.

WORK UNIT NUMBER 10

TITLE: Quantum Dynamics of Charge-Density Waves

SENIOR PRINCIPAL INVESTIGATOR:

J. R. Tucker, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. H. Miller, Jr., IBM Postdoctoral Fellow
W. G. Lyons, Research Assistant

SCIENTIFIC OBJECTIVE:

The goal of this research is to understand the basic mechanism of charge density wave (CDW) transport in the quasi-one-dimensional metals $NbSe_3$, TaS_3 , and similar materials. The motion of CDWs represents the only known example of current flow by a moving quantum ground state, apart from superconductivity. John Bardeen has proposed that CDW acceleration in an electric field takes place via a Zener tunneling process [9] and that the ac response can be predicted by applying the photon-assisted tunneling theory originally developed for superconductor-insulator-superconductor (SIS) millimeter wave mixers [10,11]. If this interpretation is correct, CDW materials could become important systems for use as detectors and mixers, as well as for basic studies of macroscopic quantum tunneling. An extensive experimental program is conducted in our laboratory to characterize the dynamics of CDW motion and to test the predictions of the tunneling theory.

SUMMARY OF RESEARCH:

The initial phase of our research on CDW systems was culminated this year with a complete study of TaS_3 [3]. Essentially, all of our results are in detailed and quantitative agreement with the tunneling theory predictions, including the:

(1) dc I-V relation as a function of electric field

(2) linear ac conductivity as a function of dc field and ac frequencies 1 MHz $\lesssim \nu \lesssim$ 1000 MHZ

(3) direct mixing (rectification) as a function of dc field and ac frequencies 1 MHz $\lesssim \nu \lesssim$ 1000 MHz

(4) harmonic mixing as a function of dc field and ac frequencies 1 MHz $\lesssim \nu \lesssim$ 1000 MHz

(5) third harmonic generation as a function of ac frequencies 1 MHz $\lesssim \nu \lesssim$ 1000 MHz

These measurements constitute a virtually complete characterization of the linear and nonlinear ac response throughout the entire experimental phase space of interest. Perhaps the single most important result of this series of experiments is the complete absence of an internal phase-shift in harmonic mixing, including regions where the linear response shows large phase-shifts at one or both applied frequencies. It seems inconceivable that this prediction of the tunneling theory could be obtained from **any** classical model.

We also performed a series of experiments designed to characterize the large-signal as well as the small-signal ac response in the presence of a dc field [4]. A major result was the discovery of a new low-frequency scale above which the ac and dc motions are effectively decoupled for dc fields $E<E_t$ below threshold. Very recently, we have shown that this ac-dc decoupling frequency is the same as the dielectric relaxation frequency characterized by the Bell Laboratories group at very low temperatures; and we were able to explain their results numerically with a simple extension of our model [8].

Another series of experiments was performed to test particular relationships that are predicted by the tunneling theory to be independent of temperature and material [5]. These relationships were indeed found to hold over wide temperature ranges for all three CDW transitions in $NbSe_3$ and TaS_3. Also, very recently we have begun to characterize the current oscillations which accompany dc motion and the "Shapiro steps" that are induced by locking to an external ac signal [6,7]. We found that these features could be accounted for very simply by our model, contrary to previous claims that infinite internal degrees of freedom must be included in a theoretical description.

OTHER SIGNIFICANT ACCOMPLISHMENTS:

Ultra-low noise SIS millimeter wave receivers are now in regular use on many astronomical telescopes and under continuing development in laboratories around the world. The operation of these devices, which now approach the fundamental noise limit imposed by the Heisenberg uncertainty principle, is based upon the predictions of the photon-assisted tunneling theory. Popular accounts of this work have recently appeared in *Physics Today*, pp. 58-62, March 1986, and in *Scientific American*, pp. 97-102, May 1986. A complete scientific review of this field has been written by the principal investigator under JSEP support, along with M. J. Feldman, and published this year in *Reviews of Modern Physics*.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] J. H. Miller, Jr., "Quantum tunneling of charge density waves in quasi-one-dimensional conductors," Ph.D. dissertation, April 1985. (JSEP)

[2] J. R. Tucker and M. J. Feldman, "Quantum detection at millimeter wavelengths," *Rev. Mod. Phys.*, vol. 57, p. 1055, October 1985. (JSEP)

[3] J. H. Miller, Jr., R. E. Thorne, W. G. Lyons, J. R. Tucker, and J. Bardeen, "Dynamics of charge-density waves in orthorhombic TaS_3," *Phys. Rev.*, vol. B31, p. 5229, 1985. (JSEP, NSF)

[4] W. G. Lyons, R. E. Thorne, J. H. Miller, Jr., and J. R. Tucker, "Ac-dc coupling and polarization for charge density waves in TaS_3," *Phys. Rev.*, vol. B31, p. 6797, 1985. (JSEP, NSF)

[5] R. E. Thorne, J. H. Miller, Jr., W. G. Lyons, J. W. Lyding, and J. R. Tucker, "Macroscopic quantum tunneling in quasi-one-dimensional metals. I. experiment," *Phys. Rev. Lett.*, vol. 55, p. 1006, 1985. (JSEP)

[6] R. E. Thorne, J. R. Tucker, J. Bardeen, S. E. Brown, and G. Grüner, "Phase-locking in charge density wave transport," *Phys. Rev. B* (May 15, 1986, in press). (JSEP)

[7] R. E. Thorne, W. G. Lyons, J. H. Miller, Jr., J. W. Lyding, and J. R. Tucker, "Current oscillations in charge density wave transport," *Phys. Rev. B* (submitted). (JSEP)

[8] J. R. Tucker, W. G. Lyons, J. H. Miller, Jr., R. E. Thorne, and J. W. Lyding, "Origin of the dielectric relaxation frequency and threshold field in sliding charge density wave systems," *Phys. Rev. Lett.* (submitted). (JSEP/NSF)

REFERENCES:

[9] J. Bardeen, "Theory of non-ohmic conduction from charge-density waves in $NbSe_3$," *Phys. Rev. Lett.*, vol. 42, p. 1498, 1979.

[10] J. Bardeen, "Tunneling theory of charge-density wave depinning," *Phys. Rev. Lett.*, vol. 45, p. 1978, 1980.

[11] J. R. Tucker, "Quantum limited detection in tunnel junction mixers," *IEEE J. Quantum Electron.*, vol. QE-15, p. 1234, 1979.

WORK UNIT NUMBER 11

TITLE: Excited State Chemistry in Gases

SENIOR PRINCIPAL INVESTIGATORS:

J. T. Verdeyen, Research Professor
J. G. Eden, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

C. C. Abele, Research Assistant
K. N. Nordheden, Research Assistant
L. J. Overzet, Research Assistant
J. H. Beberman, Research Assistant

SCIENTIFIC OBJECTIVE:

The general objective of this research unit is to study the interaction of excited molecules, atoms, or molecular fragments with solid surfaces with particular emphasis on the etching or growth of semiconducting materials. The excited species may be produced by a discharge, electron beam, ultraviolet or visible photons, or combinations of the three. Inasmuch as these excitation means produce an environment which is far from thermodynamic equilibrium, one can expect processes which deviate considerably from that found in conventional chemical processing. Our immediate experimental goals are to utilize many of the modern sophisticated diagnostic tools, such as laser-induced fluorescence, optogalvanic spectroscopy, mass spectroscopy, and Raman spectroscopy to elucidate the physical processes occurring in the volume adjacent to the surface being etched or grown. One further goal is to grow (by laser or discharge techniques) electronic materials and structures which are difficult to fabricate by conventional means.

SUMMARY OF RESEARCH:

Discharge Work—Etching

It has been found that the addition of O_2 to NF_3 discharges results in an increase in etching of silicon by factors of 3-4. A similar effect is well documented in the case of $CF_4 + O_2$ discharges and can be partially attributed to an enhancement of the dissociation rate of the fluorine donor. In the case of O_2 added to NF_3, there is little if any change in the dissociation of the donor (possibly even a slight decrease), but still the etch rate of Si more than quadruples.

It appears that this is due to the chemical reaction of the atomic oxygen with the products of the NF_3 system, NF and NF_2, which liberates more fluorine and recycles the oxygen. The results of this work have been accepted for publication in the *Journal of the Electrochemical Society*.

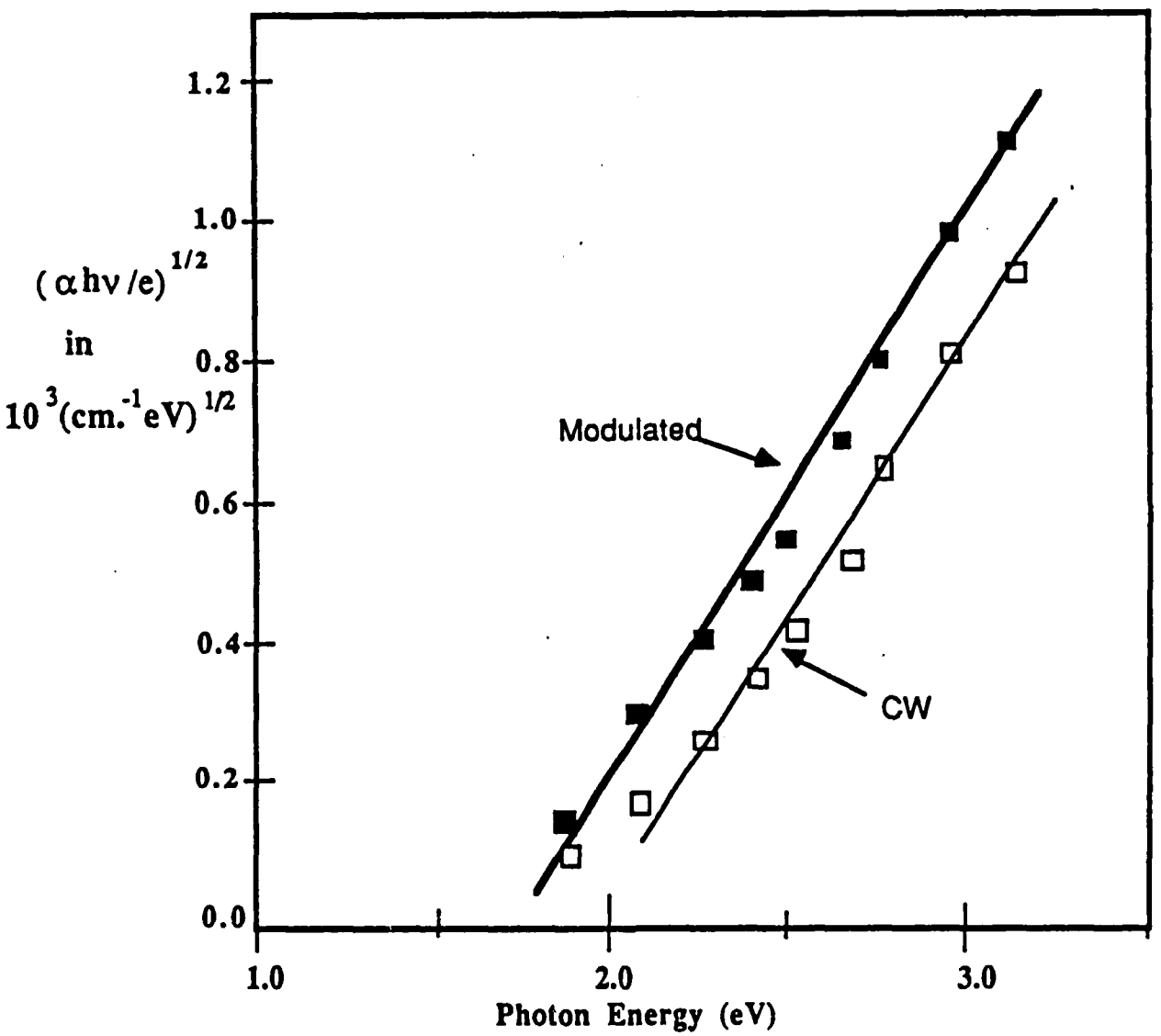

Fig. 1. Tauc Plot for the amorphous silicon films.

Modulation Effects in Discharge

It has been found that the use of square-wave modulated RF discharges makes a dramatic difference in the characteristics of plasmas used to grow hydrogenated amorphous silicon films. In the case of a 1% silane in helium mixture, the time averaged electron density for a square-wave modulated discharge can be as much as a factor of 3-4 times that of one excited in the CW fashion if the modulation rate is ~200 Hz. It is not clear why this effect occurs since the time scale does not coincide (even remotely) with the residence time nor with any characteristic plasma loss time constant. Nevertheless, the films deposited under the modulated excitation are "better" in the sense of having a higher absorption coefficient and a lower bandgap. This is shown in Figure 1.

Laser Growth of Films

The detection of ppm concentrations of AsH_3 in He by laser-induced breakdown has been demonstrated. Efforts are now being made to extend this work to the ppb level and to other molecules of interest such as PH_3 and B_2H_6.

Also, experiments have been conducted in which Si_2H_6 is pyrolyzed while the substrate is illuminated with low-fluence ($<20\ mj - cm^{-2}$) excimer laser ($\lambda = 193$ nm) radiation. Not only is the Si film growth rate enhanced in this way, but preliminary x-ray studies of the films grown on various substrates indicate that the presence of UV radiation results in the growth of epitaxial, rather than polycrystalline, films.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] K. E. Greenberg and J. T. Verdeyen, "Kinetic processes in NF_3 etchant gas discharges," *J. Appl. Phys.*, vol. 57, no. 5, pp. 1596-1601, 1985. (JSEP)

[2] K. J. Nordheden and J. T. Verdeyen, "The effect of oxygen on the etch rate of NF_3 discharges," accepted for publication in *J. Electrochemical Soc.* (JSEP)

[3] J. F. Osmundsen, C. C. Abele, and J. G. Eden, "Multiphoton dissociation of GeH_4: Ultraviolet emission spectrum of GeH," *J. Chem. Phys.*, vol. 83, pp. 2159-2161, 1985. (JSEP)

Theses:

[4] C. C. Abele, "Metal Films on GaAs by Multiphoton Ionization of Column III Alkyls," M.S. Thesis, University of Illinois at Urbana-Champaign, Department of Electrical and Computer Engineering, Sept. 1985.

WORK UNIT NUMBER 12

TITLE: Electromagnetic Radiation and Scattering

SENIOR PRINCIPAL INVESTIGATOR:

R. Mittra, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

Z. Pantic, Visiting Research Associate
C. Chan, Graduate Student
A. Chang, Graduate Student
T. Cwik, Graduate Student
E. Farr, Graduate Student
R. Hall, Graduate Student
R. Jorgenson, Graduate Student
J. Joseph, Graduate Student
K. Merewether, Graduate Student
G. Salo, Graduate Student

SCIENTIFIC OBJECTIVES:

There are three principal objectives of this effort. The first is to develop efficient iterative techniques for solving the problems of electromagnetic scattering and coupling into complex structures. The second is to study techniques for reducing the radar cross-section of targets. The third is to analyze frequency selective surfaces (FSS) for radomes and other antenna applications.

SUMMARY OF RESEARCH:

In this project we have been concentrating on three different aspects of electromagnetic scattering and coupling problems. The first of these is aimed toward developing analytical and numerical techniques for solving large body coupling and scattering problems. The second involves a study of techniques for reducing the Radar Cross-section of complex targets by loading them with either a resistive sheet or with a lossy dielectric or magnetic material that may be arbitrarily inhomogeneous. The third area of investigation involves the study of radome antennas that employ frequency selective surfaces.

During the last twelve months, we have carried out a systematic study of a number of different iteration algorithms, including the Conjugate Gradient Method (CGM) and the Spectral-Iterative Technique (SIT), for solving electromagnetic scattering and radiation problems; we have also investigated several variations of these two methods. We have studied the convergence behavior of CGM for a large number of test cases and have developed a good understanding of this behavior and its relationship to the condition number of the operator equation whose solution is being sought via the iteration technique. The results of this study have been summarized in two papers [7-8].

A block iteration approach for solving matrix equations has been developed. An important feature of this approach is that, unlike the conventional Jacobi iteration procedure, the convergence of the block iteration procedure can be unconditionally guaranteed. The block iteration approach has been successfully applied to a number of representative scattering problems. This iteration

approach has the capability of taking advantage of the availability of a good initial guess, be it derived from the application of an asymptotic technique, e.g., the geometrical theory of diffraction, or from the solution obtained previously for an adjacent incident angle or frequency step. The investigation of this approach will be continued in the future.

Another aspect of the RCS research was concerned with the problem of scattering center analysis of radar targets using the Prony's method. A method for identifying the scattering centers of an object from its RCS characteristics has been developed [9].

The investigation of frequency selective surfaces (FSS) has been carried out using the conjugate gradient iteration procedure and the Spectral Galerkin Method. FSS structures backed by dielectric substrates and multiple FSS screens have been investigated [10]. Techniques have been developed for studying the adaptive FSS screens whose scattering characteristics can be modified by implanting controllable active devices on the screens. The Spectral Galerkin approach to solving the FSS problem appears to be adaptable to the block iteration procedure [5]. The combination of the two methods would appear to be expressly suited for addressing the finite and curved FSS problems that require a rather large number of unknowns and may not be best approached via the use of the iteration procedure [6].

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

We have carried out an investigation of the convergence properties of the iteration procedures and have related the convergence rates to the condition number of the operator being inverted in connection with the scattering problem under investigation. We have introduced a new block iteration procedure which does not suffer from convergence difficulties typically found in other commonly used iteration procedures, e.g., Jacobi iteration. We have also shown how the Galerkin method can be combined with the block iteration procedure, and the combinational approach applied to multiple incident angle problem. We have developed techniques for solving the FSS problem with arbitrary apertures or patches and have initiated the investigation of curved and finite FSS screens.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] A. F. Peterson and R. Mittra, "Method of conjugate gradients for the numerical solution of large-body electromagnetic scattering problems," *J. Optical Society of America A:* Special Issue on Direct Problems in Propagation and Scattering, vol. 2, no. 6, pp. 971-977, June 1985. (JSEP)

[2] R. Mittra, "Numerical solution of radiation and scattering problems involving electrically large bodies," in *Proc. 1985 Int. Symp. on Antennas and EM Theory*, Beijing, China, Aug. 26-28, 1985, pp. 39-42. (JSEP)

[3] R. C. Hall and R. Mittra, "Scattering from a periodic array of resistive strips," *IEEE Trans. Antennas & Propagat.*, vol. AP-33, no. 9, pp. 1009-1011, Sept. 1985. (JSEP)

[4] A. F. Peterson and R. Mittra, "On the implementation and performance of iterative methods for computational electromagnetics," EMC Report No. 85-9, Dec. 1985. (ONR, JSEP)

[5] K. Merewether and R. Mittra. "Relative convergence of the Spectral-Galerkin solution for the frequency response characteristics of the Jerusalem cross FSS." to be presented at the 1986 IEEE AP-S/URSI Symposium in Philadelphia, PA in June 1986. (JSEP)

[6] R. Kastner and R. Mittra. "Iterative analysis of finite-sized planar frequency selective surfaces with rectangular patches or perforations." submitted to *IEEE Trans. on Antennas & Propagation*. (JSEP)

[7] R. Mittra and C. Chan. "Iterative approaches to the solution of electromagnetic boundary value problems." submitted to Special Issue of *Electromagnetics*. (JSEP)

[8] A. F. Peterson and R. Mittra. "Iterative computational methods for EM scattering from individual or periodic structures." to be submitted to *IEEE Journal of Oceanic Engineering*. (JSEP)

[9] M. P. Hurst and R. Mittra. "Scattering center analysis via Prony's method." submitted to *IEEE Trans. on Antennas & Propagation*. (JSEP)

[10] T. Cwik and R. Mittra. "Scattering from general periodic screens." submitted to Special Issue of *Electromagnetics*. (JSEP)

Thesis:

[11] A. Peterson. "On the Implementation and Performance of Iterative Methods for Computational Electromagnetics." Ph.D. Thesis, University of Illinois at Urbana-Champaign, Dec. 1985.

ADDITIONAL INFORMATION:

Awards and Honors:
Raj Mittra

Fellow, Institute of Electrical and Electronics Engineers
J. S. Guggenheim Foundation Fellowship
IEEE Distinguished Lecturer for Europe
AP-S Distinguished Lecturer
AP-S Best Paper Award
Past President, IEEE Antennas and Propagation Society
Past Editor, IEEE Transactions on Antennas and Propagation
Certificate of Recognition, National Aeronautics and Space Administration
Past Member, Editorial Board, Space Communication and Broadcasting
IEEE Centennial Medal Recipient
Certificate of Recognition and Award, Jet Propulsion Laboratory
Certificate of Recognition, IEEE AP-S Society

WORK UNIT NUMBER 13

TITLE: Millimeter and Submillimeter Wave Integrated Circuits

SENIOR PRINCIPAL INVESTIGATOR:

R. Mittra, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

Z. Pantic, Visiting Research Associate
J. Nasalski, Visiting Scholar
A. Ali, Graduate Fellow
E. Farr, Graduate Student
G. Wilkins, Research Fellow

SCIENTIFIC OBJECTIVE:

Effective utilization of the millimeter-wave (mm-wave) spectrum for communication, radar, and electronic counter measure, and for several other applications, depends rather critically on the development of reliable, low cost, planar-integrated circuits. A major objective of our effort is the development of guiding structures and associated components for millimeter and submillimeter wave integrated circuits.

Successful development of these waveguides and associated components requires the use of sophisticated analytical tools capable of handling complex structures comprising dielectric rods and substrates of various cross-sections, with and without metallic shields. The discontinuities in these waveguides, that are inevitably present when a circuit such as a filter, a transition, or an oscillator is integrated in a monolithic system, pose an even more challenging problem to the designer of the system. The availability of computer-aided design tools offers great help to the designer, and a major objective of our effort is to develop such tools.

Since few reliable and efficient analytical techniques are currently available for investigating planar inhomogeneous waveguides and discontinuities that can often support higher order modes, it is essential that the analytical methods we develop be thoroughly tested experimentally. For this reason, we also plan to pursue an experimental program that would support and complement the theoretical studies.

SUMMARY OF RESEARCH:

During the past grant period we have investigated the modal characteristics of printed circuit transmission lines using analytical and numerical techniques and have applied the mode-matching procedure to the solution of discontinuity problems arising in the design of transitions between active devices and microstrip lines [5]. We have also been developing [14] a finite element technique for analyzing planar transmission lines of arbitrary cross-sections that may be filled with an arbitrarily inhomogeneous medium. The results derived from the theoretical analyses described above have been verified experimentally [6], and good agreement has been found for simple models of the transition. Future work in this area will be addressing the problem of modeling of other types of discontinuities in planar transmission lines.

In the process of applying the mode-matching procedure to the discontinuity problems, it was discovered that the higher order modes for the microstrip lines, computed by using the available techniques, were not sufficiently accurate, as they did not fully satisfy the theoretical orthogonality criterion. This has led us to investigate the problem of accurate numerical solution of finline and microstrip modes [2].

The case of anisotropic substrates in coplanar transmission lines has been studied [4,15]. Such transmission lines find important applications in shunt mounting of active devices, and the anisotropic substrates provide added flexibility over the conventional isotropic substrates.

Dielectric antenna structures that are compatible with planar transmission lines have been investigated [13], and a survey of various antenna configurations and their properties has been carried out. The problem of designing finline FET amplifiers has been studied and some of the crucial issues have been identified [16].

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

We have developed techniques that would permit us to compute the higher order modes in planar waveguides in an accurate manner. The availability of higher order modes would enable us to solve various types of discontinuity problems, e.g., a transition between a FET device and a transmission line connecting it to a source or an antenna in a more reliable manner than has been possible in the past.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] S. H. Doran and R. Mittra, "An experimental study of dielectric rod antennas for millimeter-wave imaging applications," EMC Report No. 85-3, Mar. 1985. (ARO/JSEP)

[2] E. Farr, K. Webb, and R. Mittra, "Studies in fin-line antenna design for imaging array applications," *AEÜ*, Band 39, Heft 2, pp. 87-89, Mar./Apr. 1985. (JSEP)

[3] T. Kitazawa and R. Mittra, "Quasistatic characteristics of asymmetrical and coupled coplanar-type transmission lines," EMC Report No. 85-4, Apr. 1985. (ARO/JSEP)

[4] T. Kitazawa and R. Mittra, "Analysis of asymmetric coupled striplines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 7, pp. 643-646, July 1985. (JSEP)

[5] E. Farr, "An investigation of model characteristics and discontinuities in printed circuit transmission lines," Ph.D. Thesis, University of Illinois at Urbana-Champaign, Aug. 1985. (JSEP)

[6] U. Feldman and R. Mittra, "Characterization of microstrip discontinuities," EMC Report No. 85-6, Sept. 1985. (JSEP)

[7] T. Kitazawa and R. Mittra, "Quasi-static characteristics of asymmetrical and coupled coplanar-type transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 9, pp. 771-778, Sept. 1985. (JSEP)

[8] K. J. Webb and R. Mittra, "A variational solution of the fin-line discontinuity problem," in *Proc. 15th European Microwave Conf.*, Paris, France, Sept. 9-13, 1985, pp. 311-316. (JSEP)

[9] K. J. Webb and R. Mittra, "Solution of the finline step-discontinuity problem using the generalized variational technique," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 10, pp. 1004-1010, Oct. 1985. (JSEP)

[10] R. Mittra, "Millimeter-wave integrated circuits," EMC Report No. 85-8, Oct. 1985. (ARO/JSEP)

[11] Z. Pantic and R. Mittra, "Quasi-TEM analysis of microwave transmission lines by the finite element method," EMC Report No. 86-2, Feb. 1986. (ARO/JSEP)

[12] T. Kitazawa, Y. Hayashi and R. Mittra, "Asymmetrical coupled coplanar-type transmission lines with anisotropic substrates," EMC Report No. 86-3, Feb. 1986. (ARO/JSEP)

[13] G. M. Wilkins and R. Mittra, "Dielectric Antennas for Millimeter-Wave Applications," to be a EMC Technical Report, University of Illinois at Urbana-Champaign, June 1986. (JSEP)

[14] Z. Pantic and R. Mittra, "Quasi-TEM analysis of microwave transmission lines by the finite element method," to be published in *IEEE Trans. Microwave Theory Tech. (JSEP)*

[15] T. Kitazawa, Y. Hayashi, and R. Mittra, "Asymmetrical coupled coplanar-type transmission lines with anisotropic substrates," to be published in *IEE. (JSEP)*

[16] K. J. Webb and R. Mittra, "Finline Ka-Band FET amplifier study" to be published.

Theses:

[17] E. Farr, "An Investigation of Modal Characteristics and Discontinuities in Printed Circuit Transmission Lines," Ph.D. Thesis, University of Illinois at Urbana-Champaign, Aug. 1985.

[18] U. Feldman, "Characterization of Microstrip Discontinuities in the Time and Frequency Domains," Master's Thesis, University of Illinois at Urbana-Champaign, June 1985.

ADDITIONAL INFORMATION:

Awards and Honors:
Raj Mittra

Fellow, Institute of Electrical and Electronics Engineers
J. S. Guggenheim Foundation Fellowship
IEEE Distinguished Lecturer for Europe
AP-S Distinguished Lecturer
AP-S Best Paper Award
Past President, IEEE Antennas and Propagation Society
Past Editor, IEEE Transactions on Antennas and Propagation
Certificate of Recognition, National Aeronautics and Space Administration
Past Member, Editorial Board, Space Communication and Broadcasting
IEEE Centennial Medal Recipient
Certificate of Recognition and Award, Jet Propulsion Laboratory
Certificate of Recognition, IEEE AP-S Society

WORK UNIT NUMBER 14

TITLE: Control and Decision Strategies for Systems under Imperfect Information

SENIOR PRINCIPAL INVESTIGATORS:

J. B. Cruz, Jr., Research Professor
W.R. Perkins, Research Professor
P. V. Kokotovic, Research Professor
N. Wax, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

P. R. Kumar, Research Associate Professor
K. Poolla, Research Assistant Professor
D. Connors, Research Assistant
B. D. Riedle, Research Assistant
T. Ting, Research Assistant
P. W. West, Research Assistant

SCIENTIFIC OBJECTIVE:

Problems of control systems under imperfect information arise in a variety of applications. Computer control of aircraft, electronic guidance and navigation of missiles and submarines, and fire control systems are typical areas of application. Uncertainties arise because of unknown system parameters, unknown signal environments, and hardware tolerances. Related complexities arise in situations involving multiple system performance criteria and multiple decision agents having access to different information sets. In addition, such systems may consist of interconnections of systems, i.e., be modeled as a large-scale system.

The principal objective of this research unit has been to gain a basic understanding of the behavior and control of complex systems containing uncertainty. Conceptual, analytical, and computational tools fundamental to the synthesis of controllers and control strategies for such systems have been developed. Stochastic adaptive systems, robust reduced-order adaptive systems, sensitivity, and nonlinear systems have received specific attention.

SUMMARY OF RESEARCH:

During the past year, we have continued our research activities on the fundamental study of the role of modeling and information uncertainties in complex systems, specifically in the context of stochastic adaptive control, robust reduced-order adaptive control, and sensitivity and robustness of multivariable linear systems.

In adaptive control, one area of focus has been the further study of our new stability criteria, developed during the last two years, for systems subjected to parameter drifts. Our first set of results has identified most common instability mechanisms which arise in adaptive control when disturbances and or unmodeled dynamics (parasitics) are present. The first type of instability, *parameter drift*, has been known for some time and can occur when bounded disturbances are present. *Linear instability* is due to high controller gains which excite the parasitics and lead to instability. In this case the feedback loop is unstable even with fixed gains, that is, with adaptation switched off. The third type, *fast adaptation instability*, can arise when the speed of adaptation is

high and parasitics are present. *High frequency instability* is the fourth type of instability and is due to the interaction of high frequency reference inputs with the parasitics. In contrast to *linear* instability, *fast adaptation* and *high frequency* instabilities disappear when the adaptation is switched off. The fifth type of instability is *throughput instability*, which is due to the parasitics in the direct path from the input to the output.

The understanding of the instability mechanisms has led us to the second set of results which counteract the instabilities with a modified adaptation law. This modification guarantees the existence of a large attractivity region within which the adaptation algorithm converges to a much smaller residual set, in spite of unmodeled dynamics and bounded disturbances.

Our most recent result is a new stability-instability condition which replaces the old strict positive realness condition. The old condition was based on the assumption of matchable plants, which is unrealistic and must be abandoned in applications. Our new condition shows that the slow adaptation will be exponentially stable even if the relevant transfer function Z(s) is not positive real, provided that the input signal contains more energy in the frequency range of ω where $\mathrm{Re}\, Z(j\omega) > 0$ than in the range where $\mathrm{Re}\, Z(j\omega) < 0$. Moreover, we show that the adaptation is unstable if there is more signal energy for ω where $\mathrm{Re}\, Z(j\omega) < 0$. We have thus established the existence of a sharp stability-instability boundary and have given a simple criterion how to find it.

Over the past several years, we have also been actively investigating the problems of robustness in feedback systems. In particular, our research is motivated by fundamental questions such as: What can and cannot be achieved by linear time-invariant feedback? When is it advantageous to use nonlinear controllers? In this connection we have obtained some striking results. For instance, we have shown that as far as the problem of robust stabilization of a family of plants with unstructured uncertainty is concerned, the best controllers are necessarily linear and time-invariant. We have also shown that in a precise technical sense, the small-gain theorem is both necessary and sufficient.

We have also investigated maximal robustness properties of distributed systems. We have obtained formulae that demonstrate the deterioration of robustness margins as an explicit function of sensor delay. Thus, in particular for delay systems, we can quantitatively determine how "bad" the plant is in the context of robust stabilization.

We have continued work on several different problems in nonlinear system theory, namely on methods for obtaining useful exact decompositions of large-scale systems, on path controllability of input-output systems, and on the oscillations and synchronization of certain autonomous and non-autonomous systems. A "natural" extension of these problems concerns optimality: how can a system be decomposed, or controlled along a path, in the "best" possible fashion once a reasonable definition of "best" is accepted. Some recent results in optimal control systems are being studied to see if these new techniques can be applied to our investigations.

A list of papers describing these or earlier results, published since April 1985 (or yet to be published) is provided below.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] P. V. Kokotovic, "Recent trends in feedback design: An overview," *Automatica*, vol. 21, no. 3, pp. 225-236, May 1985. (JSEP NSF)

[2] B. D. Riedle and P. V. Kokotovic, "Stability analysis of an adaptive system with unmodeled dynamics," *Int. J. Contr.*, vol. 41, no. 2, pp. 389-402, 1985. (NSF/JSEP)

[3] P. V. Kokotovic, B. D. Riedle, and L. Praly, "On a stability criterion for slow adaptation," *Syst. and Contr. Lett.*, vol. 6, pp. 7-14, 1985. (JSEP/NSF)

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WORK UNIT NUMBER 15

TITLE: Implementation Constrained Decomposition and Hierarchical Control

SENIOR PRINCIPAL INVESTIGATORS:

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SCIENTIFIC OBJECTIVE:

In large-scale systems, control tasks may be decomposed and hierarchical levels may be imposed on the basis of analytically derived strategies. This project is devoted to a study of such hierarchical strategies and to associated constraints arising from computer implementation of the resulting controllers. Questions such as information flow, time scales, decentralization, and loss of feedback loops are being examined in coordinating the multiple controllers in a network.

SUMMARY OF RESEARCH:

During the past year we have conducted research on (i) time-scale properties of networks, (ii) integral manifold design of nonlinear two-time scale systems, (iii) decentralized control of large-scale systems using aggregation techniques, projective controls or dominance, (iv) computer-aided design of control systems, (v) minimax design philosophy and its applications to stochastic control systems with unknown parameters, and to communication and jamming problems with partially unknown statistics, and (vi) developing decentralized algorithms for multiple decision maker problems.

Two important characteristics of large scale systems are the presence of multiple decision makers and the decentralized nature of the information structure. In such systems different decision makers may have different objective functions, and the actions of the decision makers as a group may not be the most favorable for the optimization of a specific decision maker's objective function. When there is a single goal that is paramount or dominating among the collection of goals of individual decision makers, it is desirable to designate the associated decision-maker as the *leader* or *coordinator*. As we have shown earlier, under certain conditions the leader may be able to choose suitable strategies which are announced in advance such that the other decision-makers, called *followers*, in their search for their individual optimization goals, end up assisting the leader in optimizing the leader's objective function. Such desirable strategies are called *incentive*

strategies. We have investigated various aspects of incentive strategies for leader-follower decision hierarchies. The key to achieving the incentive property is to allow a special type of information structure for the leader whereby his control law is a mapping from the control actions of the follower into his decision space. We have studied such problems in both deterministic and stochastic dynamic contexts, and from the point of view of sensitivity.

An important aspect of decentralized and distributed large scale systems is that all decision makers may not adopt precisely the same model of the overall system, and some might even consider a simplified lower order model which is most relevant for his optimization. It is therefore imperative to develop a framework which would allow for discrepancies between individual models, some of which may be of probabilistic nature. Such a framework, which was introduced in our earlier work, was further developed this past year. Here the decision makers were allowed to adopt different prior probabilities on the uncertain quantities, and not necessarily have access to each other's specific model. We have developed different recursive schemes which involve "learning in the policy space," leading to policies that converge to the equilibrium under different stipulations on the information structure of the problem.

A second type of multimodeling or model simplification involves singular perturbations, and decomposition of the network dynamics into different time scales. In one of the papers, we discussed this approach and presented new results in the context of stochastic control, team and game problems. In another series of papers we developed a framework for analyzing time scale modeling of dynamic networks. One of our contributions is the development of a methodology whereby graphs having massive nodes connected with the 0-1 branches can be represented in simpler aggregate forms. This methodology exploits a newly established fact about the relationship between the connection density and graph eigenvalues. Using the eigenvalues as time-scale indicators, the aggregate graph interpretation is that it represents slow system-wide phenomena, while the faster phenomena are localized in the areas of denser connections. Several tests we performed on graphs of large scale systems have confirmed this modeling procedure. Yet another observation of two-time scale phenomenon has been in the field of nonlinear systems where we have approached the control design in two stages: first reaching the manifold and then satisfying a performance requirement in the manifold. We have been able to solve several nonlinear control problems of practical interest, using this general approach.

On the topic of minimax design philosophy, we have developed a number of theoretical results verifying existence of saddle points for stochastic optimization problems with nonclassical decentralized information, with one source of motivation being jamming problems arising in communications. We have also applied this philosophy to the design of controllers for stochastic systems with noisy measurements having unknown bounded noise covariances and for systems with a hybrid type of uncertainty. We have also conducted a numerical study on the comparison between performance measures under the minimax and the traditional stochastic design techniques.

On a different front, we have continued the development of the computer-aided control system design (CACSD) package L-A-S. This language, unlike menu-driven CACSD packages, provided both design support for simulation experiments with large scale systems, and a forum for algorithm-oriented control law synthesis as well. Recent developments include Multiple Operator Statements for increased efficiency in large programs, such as those describing large-scale decentralized systems. We have also continued our research on decentralized control using projective controls and dynamic or static output feedback. Projective controls provide one approach to the design of large scale systems for which limited sensor measurements are available. This approach uses output rather than full state feedback to achieve desirable response through retention of selected subspace structures that characterize the state feedback dynamics. Our recent results include extension of the method to digital controllers, and to a class of decentralized problems.

A list of papers, describing these or earlier results published since April 1985 (or yet to be published) is provided below.

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WORK UNIT NUMBER 16

TITLE: Multiple-Terminal Digital Communication Systems

SENIOR PRINCIPAL INVESTIGATORS:

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SCIENTIFIC OBJECTIVES:

Problems involving the interaction of the elements of a multiple-user communication network are among the most important and most challenging problems in electronic communications. The performance of a communication network depends in a very complex way on the routing algorithm, flow control mechanism, acknowledgment procedure, channel access protocol, error-control code, signaling scheme, receiver processing method, and synchronization technique employed in the lower three layers (network layer, data link layer, and physical layer) of the ISO layered model for the network. The objective of our research in multiple-terminal digital communications is to gain a better understanding of the interplay between these elements. Our research focusses on the issues that arise in mobile radio networks, particularly spread-spectrum radio networks, which must operate in hostile environments that include jamming and fading. This imposes additional requirements on the network in terms of robustness and survivability.

One of the objectives of our research is to develop new signaling methods and receiver processing techniques that will exploit the implicit and explicit redundancy that is present in the signals and messages. Such redundancy exists in the physical layer (diversity transmission, multipath signals, and modulation), the data link layer (error-control coding), and the network layer (redundant packets and messages). We are particularly interested in the efficient use of implicit and explicit diversity in spread-spectrum radio transmissions to improve communication performance under stressed conditions (e.g., jamming or heavy network traffic). Another objective is to develop network protocols that are compatible with and take advantage of the features of spread-spectrum modulation. Of particular interest are algorithms for distributed scheduling of transmissions. A third objective is to examine the synchronization problem for spread-spectrum radios. Efficient network operation requires fast acquisition of the spread-spectrum signals. Moreover, the acquisition and synchronization systems must be able to operate in the presence of multiple transmissions, jamming, and fading to be of any use in a military communications network.

SUMMARY OF RESEARCH:

Diversity Combining for Frequency-Hop Communications

Diversity transmission is often employed in frequency-hop systems to provide reliable communication in the presence of fading or partial-band interference. Some of the methods for combining the diversity receptions require side information regarding the presence or absence of interference. Because of implementation considerations, diversity combining techniques that do not require side information from external sources are particularly attractive. One such combining scheme, called *clipped linear combining* [25], involves clipping the output of the envelope detector of each diversity reception before it is added with the other diversity receptions. It is shown in

[25] that clipped linear combining is effective against partial-band interference. There is a practical disadvantage, however, since the clipping level depends on the average received signal voltage (in the absence of the interference) which may be difficult to measure in practice.

It is desirable to employ diversity combining techniques that do not depend on the received signal power. In one such diversity combining technique, *Viterbi's ratio threshold technique* [26]-[28], each diversity reception is determined to be accepted or rejected based on the relative values of the envelope detector outputs. More specifically, for each diversity reception, the ratio of the largest envelope detector output to the second largest envelope detector output is compared to a threshold. The diversity reception is accepted if the ratio is greater than the threshold, and rejected if the ratio is smaller than the threshold. If at least one reception is accepted, then only the accepted diversity receptions are combined. If all diversity receptions are rejected, then all of them are combined and a hard decision is made (the resulting symbol may be flagged for erasure if the decoder has a provision for correcting erasures [2], [16]).

We have computed the average probability of error for Viterbi's ratio threshold technique used in conjunction with diversity for frequency-hop communications in the presence of partial-band Gaussian interference [9], [29]. The system with binary orthogonal signaling and noncoherent demodulation is analyzed. A comparison is made between the system employing Viterbi's ratio threshold technique with linear diversity combining and the system that utilizes clipped linear combining as the diversity scheme. We allow a nonzero background or quiescent noise level to account for thermal noise in the receiver and other wideband noise sources.

Our most recent research on diversity combining is devoted to an investigation of diversity combining for channels with both fading and partial-band interference. Use of diversity in a frequency-hop spread-spectrum system provides an effective means for combatting both fading and partial-band jamming. Thus far, we have considered two different diversity combining schemes that are based on ratio statistics. The first uses a ratio threshold test in conjunction with square-law combining, and the second is based on majority-logic combining of ratio statistics. These schemes are analyzed for both Rician and Rayleigh fading channels with partial-band jamming in a recent paper[30].

Fast Frequency Hopping for Mobile Radio Applications

We have continued our investigation of the performance of a class of fast frequency hopped spread-spectrum multiple-access communication schemes proposed for mobile radio communications. We have studied the performance of the sub-optimum receiver (derived in earlier work) when it uses hard decisions instead of soft decisions on each hop. Both the additive white Gaussian noise channel and the nonselective Rayleigh fading channel have been considered. We have also analyzed the performance of this receiver when interfering signals from other users are present. Analytical results have been obtained for both the nonfaded and the nonselective Rayleigh faded channel [4]. These results indicate that the performance of this receiver is somewhat different from the performance of previously considered receivers for this system. We have also obtained new results on the design of frequency-hopping patterns for these systems.

Spread-Spectrum Multiple-Access Communication for the Low Frequency Band

We have continued our investigation of DS SSMA communication over the low frequency (LF) band. We have derived a locally optimum receiver for such a system operating in a mixture of Gaussian and impulsive noise [31], [33]. The receiver consists of a bandpass correlator followed by a sampler, a zero-memory nonlinearity, and M discrete-time matched filters. The design of codes for such systems has also been studied [32]. More recently, we have studied the performance of such a receiver when the optimum nonlinearity is replaced by more easily realizable nonlinearities such as limiting amplifiers, hard limiters, and hole-punchers. Our results indicate that performance (as measured by the signal-to-noise ratio) is degraded only slightly when such nonlinearities are used and that the performance is not very critically dependent on the parameters defining these

nonlinearities. Error probability as a performance measure is being studied at present. Preliminary conclusions are that performance is degraded very slightly when suboptimum nonlinearities are used.

Transmission Scheduling and Broadcasting in Radio Networks

We have made progress on the problem of scheduling transmissions in a mobile packet radio network to avoid primary collisions. The minimal schedule length necessary to support a given set of conversations is essentially given by the multichromatic index of a graph. Edmonds' theory of weighted nonbipartite matching yields a set of linear inequalities which characterize the minimal schedule length. We have recently discovered an efficient polynomial time algorithm for computing a schedule of minimal length which is guaranteed to be no more than 50% longer than optimal and which is usually nearly optimal [34]. More recently, we have discovered a more complicated polynomial-time algorithm for the optimal link scheduling problem [5]. The algorithm is based on the work of Grotschel, Lovasz, and Schrijver and the work of Padberg and Rao, as well as on the work of Edmonds. The algorithm proves false the previously held belief that the scheduling problem is NP-complete. An extension of the algorithm of the algorithm has been given which produces schedules, in polynomial time, on the basis of given *end-to-end* demands.

In another line of JSEP-funded research, we have shown how the theory of stochastic approximation can be used to fruitfully study adaptive control of retransmission probabilities [35]. A quite general family of retransmission control strategies was introduced such that, on the basis of very limited feedback, the transmission probabilities of various stations can be controlled.

Issues of fairness and priorities are addressed through the introduction of a cost function which the stations endeavor to minimize in a distributed fashion. The estimators appear to be quite effective in simulations. The use of stochastic approximation provides a fairly systematic approach which can be applied as well to the control of transmission power, code rates, etc. These possibilities deserve further study.

Clustering Algorithms for Packet Radio Networks

We have begun a study of algorithms for organizing a packet radio network into overlapping clusters. Two strategies were proposed and compared [36]. The strategies incorporate heuristics for generating priorities which determine which nodes will become cluster heads. Simulations were used to generate trade-off curves for the strategies. A small mean distance to the nearest cluster head can be traded off to obtain a low density of cluster heads. We found that some clustering strategies tend to have more favorable trade-off curves.

Sequential Decoding for Channels with Unknown or Time-Varying Parameters

Sequential decoding is a practical decoding algorithm for codes with a tree or trellis structure. The computational efficiency of this algorithm, as well as the probability of correct decoding, depends critically on the use of a metric that matches the channel parameters. If the channel parameters are known, one may use the Fano metric [37], which achieves all rates up to the computational cutoff rate within finite expected computation per decoded source digit. If the channel parameters are unknown but stationary, one may first estimate the channel parameters through the use of test sequences and then use the appropriate Fano metric. If the channel characteristics are changing slowly in time, the estimation of the channel parameters and the updating of the metric may be repeated periodically.

An alternative to the above approach is to use a metric that has a built-in procedure for estimating the channel transition probabilities. Here the idea is to find a metric which is universally good, in the sense that, for any given channel, the same metric achieves all rates up to the cutoff rate of that channel. We have found such a metric, which is closely related to Goppa's method of maximum mutual information decoding [38], and analyzed its performance.

In essence, a metric is just a function that measures the statistical correlation between a hypothetical channel input sequence and the observed channel output sequence. The universal metric mentioned above uses the empirical mutual information as its measure of correlation. Generally speaking, the higher the rate the better the correlation estimate has to be; otherwise, the decoding complexity becomes unbounded at rates strictly below the cutoff rate (the theoretically possible highest rate). The accuracy of the correlation estimate can be improved by increasing the length of sequences over which estimation is carried out. In fact, we have shown that, if the underlying channel is stationary, this metric can be used at rates arbitrarily close to the cutoff rate of the underlying channel by computing the metric over sufficiently long, but always finite, sequences. The length of sequences over which the metric is computed should be chosen so that it is enough to guarantee finite computational complexity, but not much longer because the computation of the metric over long sequences may increase both decoding complexity and delay.

If the underlying channel is time-varying, the analysis of this metric is more complicated. However, it is easy to see that the metric will still be useful so long as the channel parameters do not change appreciably over the length of sequences over which the metric is computed.

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WORK UNIT NUMBER 17

TITLE: Digital Detection and Estimation

SENIOR PRINCIPAL INVESTIGATOR:

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SCIENTIFIC PERSONNEL AND TITLES:

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S. Zabin, Research Assistant

SCIENTIFIC OBJECTIVE:

The primary goal of this research is the development of practical and efficient implementations for signal detection and estimation systems with potential applications to communication receivers, sonar and radar tracking and detection, and other statistical signal-processing functions. The main emphasis is on the development of techniques for the design and analysis of digital systems for use in such applications. Particular attention is paid to situations in which signal and noise models do not obey standard assumptions or in which accurate modeling is not possible. Such situations invite the utilization of nonlinear, robust, adaptive, and/or nonparametric systems which, while exhibiting superior performance, often require complex structures for exact implementation. Advances in integrated circuitry have made practical the approximation of such structures with digital systems; therefore, this study is motivated in part by the desire to utilize fully the flexibility and power of the new technology.

SUMMARY OF RESEARCH:

Our JSEP-sponsored research during this reporting period has been focused primarily on two problems: (1) performance evaluation of direct-sequence spread-spectrum multiple-access (DS/SSMA) communications in non-Gaussian noise environments and (2) development and analysis of estimation schemes for identifying impulsive noise channels.

Non-Gaussian, impulsive noise is a key noise source in many multiple-access communication systems (such as military radio networks). Thus, when studying such systems, the evaluation of their performance in non-Gaussian noise is of interest. We have considered two techniques for evaluating the average error probabilities of conventional linear DS/SSMA receivers in impulsive noise--one uses a characteristic function method and is useful for small spreading sequence lengths, and the other uses a Taylor-series expansion method for longer spreading sequences. We carry these results further by considering nonlinear correlation receivers to improve the receiver performance against impulsive noise. These results indicate that substantial performance gain can be obtained by using nonlinear reception, particularly for long spreading sequences and heavily impulsive noise.

We have also considered several problems relating to the identification of impulsive noise channels. Our preliminary findings in this continuing study have shown that standard batch and recursive nonlinear identification techniques, such as maximum-likelihood and stochastic approximation methods, are insufficient for this purpose because of fundamental identifiability problems associated with these algorithms when applied to standard statistical-physical models for impulsive

estimation procedure combining the principles of moment estimation (which is consistent but highly inefficient in this model) and maximum likelihood. The result is an estimator that is both consistent and asymptotically efficient.

A further study has treated the analysis of the efficiencies of a class of multistage signal-detection algorithms. These algorithms are seen in our analysis to have efficiencies near that of the optimum sequential-probability-ratio detector while retaining the design and implementational simplicity of conventional fixed-sample-size detection algorithms. These new algorithms are particularly efficient for applications, such as search radar, in which the presence of a signal occurs rarely relative to the absence of one.

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WORK UNIT NUMBER 18

TITLE: Hierarchical Simulation and Design Verification of VLSI Circuits and Systems

SENIOR PRINCIPAL INVESTIGATORS:

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V. B. Rao, Research Assistant Professor
T. N. Trick, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

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SCIENTIFIC OBJECTIVE:

Since the introduction of the integrated circuit chip, chip complexity has doubled every two years. However, concurrent with this growth in complexity, the design cycle has lengthened and the design expense has been increasing by a factor of 3 or more about every 5 years. We are now at the point where the design of a custom VLSI circuit will require over 100 man-years with present design methodologies. Thus, the initiation of a new VLSI circuit is a very major investment risk. This trend in design complexity is a major concern of leaders in the electronics industry. New design methodologies as well as better computer-aids for the synthesis, layout, simulation, verification, and testing of VLSI systems are needed. Unfortunately, the computational complexity of the problems in this area are typically NP-complete. From the point of view of the development of design automation tools, the apparent intractability of NP-complete problems leads one to the use of suboptimal heuristic algorithms. Because of this complexity, a hierarchical approach will have to be taken in the solution of the problems in this field.

The objective of our research in this area is to study hierarchical approaches to the simulation and verification of VLSI circuit designs. In particular, models and design verification aids for the various hierarchical levels will be investigated. The trend in VLSI design is to use a top-down structured design approach in which systems are implemented by means of a number of identical cells which communicate to each other in a predefined way. It is important in the bottom-up design verification phase to be able to model and accurately simulate the timing of these communication links particularly in high-speed signal processing systems.

SUMMARY OF RESEARCH:

This past year a new DC and AC circuit model for modulation-doped GaAs FET's was developed. Other models are unnecessarily complex and have discontinuous derivatives at the boundaries between the different regions of operation. Thus, in circuit simulation, the models are very costly. Furthermore, past experience with MOSFET models has shown that models with discontinuities in their derivatives have serious convergences problems. Unfortunately, only recently have researchers discovered that these discontinuities were the source of this very serious problem which has plagued simulation experts for a decade. Our new model overcomes these difficulties, and it is simple and accurate. The model can be used for both MODFET's (HEMT's) or MOSFET's, and even though the model parameters have different interpretations for each of these transistor types, physical arguments can be made as to why the model can be used for both devices.

The model has been implemented in a parameter characterization system which consists of a HP 4145 Semiconductor Parameter Analyzer and a HP 9836 computer. An optimization routine is used to fit the model parameters to the measured device characteristics. Excellent agreement has been obtained between the measured characteristics and the model on several MODFET samples provided by Professor Morkoc.

Work has continued on the hierarchical simulation of VLSI circuits for circuit, timing, and logic analyses. Several years ago under JSEP sponsorship, we used node-tearing methods to partition large circuits hierarchically. This allowed us to (a) use block LU factorization techniques in the solution of the circuit equations, (b) declare circuits latent at higher levels in the hierarchy, and (c) reduce memory requirements. The block LU factorization of each subcircuit equations can proceed in parallel on a multiprocessor system. Recently a study was completed on the use of special purpose computer architectures for the LU factorization of this partitioned system of equations [8]. The performance of both systolic and wave-front array processors was investigated. However, the LU factorization of the interconnect equations remains a bottleneck in the effort to obtain significant speed improvement. Thus, our attention turned to decoupling methods. Unfortunately, these methods add another iteration loop to the solution process, and one must be concerned about convergence within this loop. We studied the convergence properties of two decoupling methods, an incremental Gauss-Seidel relaxation algorithm and the waveform relaxation algorithm. In the algorithms used in standard circuit simulators, the convergence depends on the local truncation error and thus the timestep can be controlled by the rate of change of the waveform. However, when relaxation techniques are employed, we found that the convergence is now a function of the coupling among the partitioned circuits. If the coupling is sufficiently weak, the time step can still be controlled by the local truncation error. However, it is not always easy to determine the degree of coupling and so the time step must not only be controlled by the local truncation error but also by the number of iterations in order to achieve good convergence [2,5]. In cases where strong coupling exists, the method can be extremely costly. Thus, the performance of these relaxation algorithms is critically dependent on the partitioning of the circuit [12]. In order to take into account the effects of coupling between neighboring partitions, a new robust overlapping relaxation method has been developed and tested [3,4,11].

Earlier, it was pointed out that in the solution of nonlinear circuit equations, the convergence of the algorithm depends on the function description of the model. We have found that piecewise linear solution techniques result in very robust algorithms [6,9]. These techniques require that the nonlinear device characteristics be described by a series of piecewise linear segments. This model is more flexible and more readily adaptable to changing technology; however, the description is not in terms of physical parameters. It may be necessary to use a physical model description externally, but internally a piecewise linear description could be generated in order to achieve reliable convergence to the solution.

At the timing level, fast switch-level timing simulation techniques have been developed. The timing information is obtained from delay tables which are compiled from a circuit simulator in which only certain primitives in the circuit are simulated [1,4,25]. The approach has been implemented in a general purpose program called MOSTIM. In another approach, parametrized delay functions derived from circuit element characteristics [21,26]. This approach has been implemented in another program called IDSIM.

At the logic level, switch-level transistor modeling has been used to extract logic expressions from transistor netlists to check for the functionality and the connectivity of the designs [27,28]. Techniques have also been developed to incorporate physical faults in the logic expressions for fault simulation [22]. The technique has been implemented in a program called EXPRESS. In addition, pipelined and distributed computer architectures have been evaluated for switch-level logic and concurrent fault simulation of the circuit [23].

In order to generate accurate timing information, it is essential to have good circuit models for the interconnect. We have developed two experimental rectangle-based circuit extractors, NPEX (for NMOS technology) and CPEX (for CMOS technology) for layouts in pure Manhattan geometry. Both NPEX and CPEX have the capability of generating output files suitable for MOSTIM, IDSIM, and EXPRESS.

We have also done some studies on synthesis techniques and PLA folding methods for VLSI design [1,10]. A computer program is being developed that takes a high-level description of a design and automatically produces a layout [7]. The design system will be coupled to the hierarchical simulation tools which we have been developing for design verification.

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WORK UNIT NUMBER 20

TITLE: Computer Architecture

SENIOR PRINCIPAL INVESTIGATORS:

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SCIENTIFIC OBJECTIVES:

This unit seeks to develop, model, and analyze efficient, high-performance computer architectures. We have identified several aspects of computer architecture for particular attention due both to their emerging importance from a technology-driven point of view and to the lack of known structures or analysis techniques for meeting our objective.

Parallel-Pipeline Architectures

This section is devoted to exploring the limits of highly concurrent VLSI processors and multiprocessors. VLSI technology affords large on-chip complexity but has relatively limited capability for interchip communication. Accordingly, there is a heavy emphasis on using on-chip storage effectively to reduce off-chip communication. Furthermore, the long access times, albeit with high bandwidth associated with off-chip requests, create the need for issuing such requests earlier to achieve effective forwarding of information to a processor so as to minimize the wait time of a highly pipelined processor. Finally, dependencies and linkages between tasks allocated to different processors must be studied to achieve minimal dependency-related performance degradation.

Memory Organizations

In recent years, the memory has become one of the most expensive parts of a typical computing system. In addition, the overall performance of a system is also primarily governed by its memory organization. Therefore, the investigation of memory organizations is essential to the development of high-performance computing systems. In particular, multiprocessor systems are becoming increasingly important due to the cost-effectiveness considerations of VLSI technology. To exploit this potential, memory system architectures must be appropriately organized for such systems. The objective of this research is to develop, model, and analyze high-performance memory organizations for multiprocessing and multiprogramming systems, including cache and virtual memories, for symbolic and numeric processing.

Parallel Algorithms and Architectures for Automatic Test Generation

With the rapid progress of VLSI technology, the problem of fault detection for logic circuits is becoming increasingly more difficult since the computational complexity of test generation is exponential with the size of the circuit. Many test generation algorithms have been proposed over the years, namely, the D-algorithm [7] and its variants such as PODEM [9] and FAN [8]. All of them have the disadvantage of being forced to make random guesses in the backward implication (or backtracing) process in order to generate test vectors at the primary inputs (PI). Following an incorrect guess, the algorithms backtrack to explore alternate solutions which slows down the test generation process immensely. In this research, we are investigating the feasibility of speeding up the test generation process by exploring efficient parallel algorithms that could be executed on parallel architectures.

SUMMARY OF RESEARCH:

Parallel-Pipeline Architectures

High-speed scalar processing is an essential characteristic of high-performance, general-purpose computer systems. Highly concurrent execution of scalar code is difficult due to data dependencies and conditional branches. We developed an architectural concept called *guarded instructions* to reduce the penalty of conditional branches in deeply pipelined processors. A code generation heuristic, the *decision tree scheduling* technique, reorders instructions in a complex of basic blocks so as to make efficient use of guarded instructions. Performance evaluation of several benchmarks were used, including a module from the UNIX kernel. Even with these difficult scalar code examples, a speedup of two is achievable by using conventional pipelined uniprocessors augmented by guard instructions, and a speedup of three or more can be achieved using processors with parallel instruction pipelines.

Memory Organizations

We have studied several numerical programs in the context of our research on virtual memory management. Our study revealed that program localities can be quantitatively recognized through some analysis of source code. Localities so identified can then be made into memory management directives to be used at execution time. This is the basic idea behind the *compiler-directed* (CD) memory management policy. Empirical results were obtained on the performance of CD and the Working Set policy in a multiprogramming system. The results show that CD outperforms WS in terms of fault rate, space time cost, and throughput characteristics. Moreover, WS is shown to lack controllability. Two anomaly types were found, both of which are exhibited by WS but not by CD.

Parallel Algorithms and Architectures for Automatic Test Generation

We have identified the lack of an efficient search technique in implementing the backtracing operation of any automatic test generation algorithm. The algorithm that we are currently investigating in this research seeks to minimize the number of backtracks by using the computational power of parallel processing and utilizing efficient search techniques from artificial intelligence. The algorithm takes the circuit under test and examines every fanout point. Based on the number of processors in the parallel architecture and their interconnection topology, a given circuit is partitioned into subcircuits which are allocated to different processors to distribute the computational load equally among them. Instead of making a random guess at the gates that can have multiple input combinations to get the same output, our proposed algorithm does not assign a fixed signal value to the inputs of these gates. We assign a Boolean variable to the signal value at the nearest fanout point in the primary input direction and propagate this value in the forward direction to the gate which needs input choices. In this way no random choices are needed, and we generate a consistent signal line value at the inputs of the goal gate. We have successfully applied our algorithm

manually on some example circuits. The next step in our research will be the implementation and evaluation of our parallel algorithm in the C++ programming language. Also, our algorithm presently generates tests for detecting stuck-at faults at logic gate, but in the future, we will extend the coverage to other fault models in MOS circuits as well [10].

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WORK UNIT NUMBER 21

TITLE: Fault-Tolerant Computer Systems

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SCIENTIFIC OBJECTIVE:

The focus of this unit is on the fundamental issues in the design and analysis of fault-tolerant computers. As computational power and the physical complexity of computer systems increase, so does the need for increased reliability and fault tolerance. In addition, there is a pressing need for systems which will continue to function under a variety of workload environments and failure conditions. We have identified several issues which require particular attention due to both technology and systems viewpoints. These approaches are necessary for realizing effective fault tolerance without extreme cost and performance penalties.

Reliable Distributed Database Systems

Recent interest in knowledge-based computing systems has resulted in new challenges concerning special-purpose database system architectures. Of specific concern to this research is the reliability of large distributed databases and the architectures that manage the data. Unfortunately, there is little published research which provides solutions to the problems of error detection and correction in database systems operating in a real-time environment. Though there is a significant body of literature regarding database recovery, almost all of the developments have concerned recovery of a backward nature, such as rollback, which is not appropriate for time-critical applications.

The goal of this research in reliable database systems is the development and analysis of both algorithms and architectures for detection and recovery of both semantic and structural errors in distributed databases appropriate for real-time applications. The approach employed in this research is the investigation into the use of algorithm-specific architectures and separate monitor processors in conjunction with our recent results concerning access path checking for concurrent detection and recovery. The unique aspects of distributed systems allowing for replicated files and processors are being investigated for recovery from exceptions. Specific applications being considered include knowledge-based, real-time control databases and distributed databases for design automation.

In addition to the research concerning concurrent detection of errors caused by hardware failures, we are investigating methods for concurrently detecting software design errors. A formal specification-based approach is being studied in which diversified representations of structure and data are created and used for real-time design error detection. The potential use of a monitor processor to check different structure representations in a distributed system is also being investigated.

Measurement and Symptom-Based Analysis of Fault Tolerant Systems

Modeling hardware and software fault tolerance is a complex analytical problem. Results on hardware and software reliability and fault tolerance based on real measurements and experiments are essential if a scientific basis is to be developed for accurate analytical modeling. This research is concerned with the development of effective models based on real failure and workload data. This work is primarily motivated by the fact that previous research shows that system reliability is a dynamic function of the level and nature of system activity as described by the system workload. These results have major significance because they indicate that (in contrast with conventional wisdom) it is not useful to push a system close to its performance limits, since the gain in performance is more than offset by degradation in reliability.

This research proposes to develop hardware and software reliability models to explicitly take the nature and level of system activity into account. These models will be based on real failure and workload data being collected on several systems on campus. IBM Cyber systems are being monitored to provide appropriate data for both model development and validation.

In addition, it is proposed to study possible cause-and-effect relationships to describe the observed workload/failure dependency. In particular, the effect of workload variations on error/fault-latency characteristics will be investigated. Finally, the use of the measured information to perform on-line diagnosis will be studied. A feasibility study based on the observed error rate and the type of activity in progress at the time of the error is proposed. The study is expected to be general so as to encompass different machine architectures and configurations.

SUMMARY OF RESEARCH:

Reliable Distributed Data Base Systems

Research has been initiated within the last year concerning both the use of replicated files and methods of access-path verification for use in fault-tolerant, real-time database systems. The problem of diagnosing differences between large replicated files has been examined and initial results obtained. A low-cost scheme has been developed for diagnosis and comparison of files based on a size $O(\log N)$ checking matrix, where N is the number of pages in the file [4,16]. The approach is applicable to situations in which communication dominates the cost of comparison and the typical number of differing pages between files is not excessively large. Elements of the checking matrix are derived from signatures associated with each page of the files to be compared. The relatively small size of the matrix allows it to be resident in main memory without the need for extra accesses to disk during normal updates of pages.

Research concerning concurrent detection of structure and semantic errors has resulted in two methods of incorporating redundancy in linked data structures [17]. The techniques do not use redundant pointers for exception detection but, rather, employ the concepts of signatured-access paths and distributed and appended checks. Signatured access paths provide for concurrent error detection by storing signatures of the information along typical traversal paths in the nil pointers of the data structures. Checking is performed by recomputing the signatures during normal database traversal and comparing with the stored signatures. An alternative has been developed in the form of distributed and appended checks. Studies have been undertaken regarding the placement and form of checks over local data structure nodes for error detection, in conjunction with the use of global checks in the form of appended data structures for error correction. Both approaches provide for concurrent verification of both structural and semantic integrity and are appropriate for real-time applications.

Some initial results have also been obtained concerning concurrent detection of software design errors [14]. A formal specification-based approach is being studied in which diversified representations of structure and data are created and used for real-time design error detection.

Measurement and Symptom-Based Analysis of Fault Tolerant Systems

Our previous studies offer considerable insight into the characterization of errors by their related symptoms. The results show that the operating environment (hardware and software) of the system and its workload have a significant impact on the occurrence of errors and the effectiveness of the recovery management. In particular, the failure rate has been explicitly related to the level and degree of interactive workload and performance measures [3,9,13]. A new model based on measured data to describe the relationship between workload complexity and the failure and recovery process has now been developed. The model is now being further tested on data from a new system. The study of cause and effect relationships has resulted in new techniques to determine fault and error latencies in production systems [1,11].

These studies indicate that there is sufficient information in the past error/recovery behavior and in the workload environment to characterize symptoms of the persistent errors. The methodology relates errors occurring in different parts of the system. The approach uses the system error rate to identify the possible relationships among seemingly isolated errors and then uses probabilistic techniques to quantify the validity and the strength of the relationships [2,7]. The feasibility of such a technique has been established using detailed error and performance data from a large CYBER system at the University of Illinois [15].

The results of this research are expected to lead to new approaches to designing fault-tolerant architectures which are capable of concurrent recognition of failure symptoms sufficiently before the actual failure.

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WORK UNIT NUMBER 22

TITLE: Efficient Computation Techniques

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SCIENTIFIC OBJECTIVE:

Current technologies require the development of efficient computational techniques and the analysis of the capabilities of various models of computation. We are concerned with the resources--such as time, equipment, memory, interconnection--that are used or needed in the algorithmic solution of given problems. This dynamic discipline, known as concrete computational complexity, not only contributes to a fundamental understanding of computing but is also extremely relevant to both hardware and software applications. It is only natural that the great technological innovations represented by Very-Large-Scale-Integration (VLSI) and the advent of computer networks have had a substantial impact on this field, opening new horizons and posing challenging problems. Much of our current research has been motivated by these innovations.

SUMMARY OF RESEARCH:

Our research has focussed on parallel and distributed computations and on combinatorial and geometric algorithms.

In the area of distributed computing, we compared two paradigms of distributed algorithms. In a *chaotic* algorithm, a processor may transmit a message whenever it wishes. In a *token* algorithm, a processor may transmit a message only when it possesses a unique token. We proved that every problem solved by a chaotic algorithm can also be solved by a token algorithm that uses, at most, three times the total number of messages in the worst case.

We have strengthened our previous results on memory requirements for agreement among fail-stop asynchronous processes that communicate via a shared memory. There is no agreement protocol that uses test-and-set operations if memory cells have only two values and two or more processes may fail. In contrast, there is a test-and-set agreement protocol if either memory cells have at least three values or at most one process may fail.

We have designed several new algorithms for important computational problems. An algorithm is in NC if on inputs of size n it uses polylog time, $O((\log n)^a)$ for a constant a, and polynomially many processors, $O(n^b)$ for a constant b. We have devised an NC algorithm for

(1) computing all roots of a polynomial with only real roots;

(2) performing depth first search of directed acyclic graphs;

(3) decomposing graphs into connected pieces ("ears"); and

(4) evaluating a straight line program over a commutative semiring.

In addition, we have developed a parallel algorithm for solving linear programs with two variables per inequality and two variables in the objective function. This algorithm uses polylog time but a superpolynomial number of processors.

We compared three important models of synchronous parallel computation: the d-dimensional iterative array (dIA), the iterative tree automaton (ITA), and the alternating Turing machine (ATM). We established the following relationships:

(1) every ATM of time complexity t(n) can be simulated by an ITA in time $O(t(n))$;

(2) every dIA of time complexity t(n) can be simulated by an ATM in time $O(t(n)^d)$; and

(3) every ITA of time complexity t(n) can be simulated by an ATM in time $O(t(n)^2)$.

A second area of research has been the design of parallel algorithms and, in particular, of VLSI algorithms, i.e., the chip implementation of networks designed for specific computations. We report the following results:

(1) We have thoroughly studied the sorting problem in VLSI. In particular, we have proposed a class of designs of a new interconnection network, the *pleated cub-connected cycles* (PCCC), which can implement stable bitonic sorting of n records of size q in area $A = O(q^2n^2/T^2)$, where T the computation time, is in the range $[\Omega(q \log^2 n), O(q\sqrt{n/(q+\log n)})]$. Thus, this network is an AT^2-optimal bitonic sorter in the synchronous VLSI model of computation. We have also presented a generalization of a known class of parallel sorting algorithms, together with a new interconnection to execute them. In a VLSI implementation, it is shown that an algorithm in the class is executable in $O(\log n)$ time by a chip occupying $O(n^2)$ area. The design is a typical instance of a "hybrid architecture," resulting from the combination of well-known VLSI networks as the orthogonal trees and the cube-connected cycles; it also provably meets the AT^2 lower bound.

(2) To maintain a database, a dictionary machine accepts a sequence of insertion, deletion, and query instructions at a constant rate. We designed two new VLSI dictionary machines on general-purpose networks that emulate the binary cube. Our dictionary machine on a shuffle-exchange network has a novel architecture that implements a macropipeline with timestamps to deliver responses in order. Our other dictionary machine on a cube-connected-cycles network stores records in order of key value along a Hamiltonian path, which we constructed explicitly.

Geometric problems occur in a large number of disciplines, like robotics, logistics, operations research, computer-aided design, graphics, etc. In this now classical area--that has been one of the main focuses of our research in the previous decade--we have obtained a number of interesting results. Range-searches are a significant class of applications; we have investigated the problems of circular range search in the plane and half-space search in 3-space. Specifically for a set of n points, we have shown that the first problem can be solved by a data structure using $O(n(\log n \log\log n)^2)$ space so that a query that returns k points is answered in optimal time $O(\log n + k)$. For the second problem, the same query behavior is obtained with a data structure using a somewhat larger amount of storage.

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WORK UNIT NUMBER 23

TITLE: Multi-Sensor Digital Array Processing

SENIOR PRINCIPAL INVESTIGATORS:

T. S. Huang, Research Professor
W. K. Jenkins, Research Professor
D. C. Munson, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. Blostein, Research Assistant
A. C. Bovik, Research Assistant
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H. H. Chen, Research Assistant
M. Desai, Research Assistant
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H. Fan, Research Assistant
G. Kakazu, Research Assistant
B. C. Mather, Research Assistant

SCIENTIFIC OBJECTIVE:

The term "multi-sensor array system" refers to a large class of remote sensing systems in which data are collected and recorded by many independent sensors, or by one sensor that is moved to different spatial positions. The recorded data are processed by a digital array algorithm to produce a high-resolution object function. Some of the more important multi-sensor array systems now in use are synthetic aperture radar (SAR), computer-aided tomography (CAT), and beamforming sonar. The objective of the research in this unit is to develop both the theory and computer verification of new signal processing methods with the goal of overcoming current limits on resolution and data throughput rates for these systems.

SUMMARY OF RESEARCH:

During the past year, our JSEP research has concentrated on image reconstruction from partial Fourier data, bandlimited extrapolation and phase retrieval, nonlinear filtering, finite register effects, and adaptive digital filtering.

SIGNIFICANT RESEARCH ACCOMPLISHMENTS:

Image Reconstruction from Partial Fourier Data

Our work in this area centered around the special problems of spotlight mode SAR operating with a narrow look angle (≤ 10 degrees), in which only a small region of the Fourier transform of the ground reflectivity function is sampled by the radar. New results have been obtained which improve both basic understanding and processing algorithms for conventional Fourier reconstruction techniques, as well as introducing some new processing algorithms which have not been used before in SAR. Recent accomplishments are summarized below:

(1) Publications [3,5,7,11,27,28] all deal with image reconstruction from partial Fourier domain data, with synthetic aperture radar as the primary application. Reference [22] presented an analysis which shows that SAR imaging and CAT scanning are mathematically similar inverse problems. These results stimulated further investigations into the use of Hankel transform (HT) techniques and convolutional back-projection (CBP) techniques for SAR [3,23,24,25]. It was discovered that both (HT) and (CBP) techniques have the capability to provide very high quality SAR imagery, although they are rather computationally intensive. It was shown that the CBP algorithm partitions easily into parallel channels suitable for multi-processor implementation, and therefore, may be a good algorithm for VLSI realizations. Reference [26] presented fundamental results on the nature of imagery that is produced from a small area of offset Fourier data, illustrating that it is the random phase nature of terrain that allows the SAR to produce images that we easily recognize. Both [22] and [26] have received considerable attention from the radar community, with [22] being reprinted in two separate IEEE Press books. The possibility of reconstructing from only the phase of the Fourier transform is explored in [7].

(2) Publications [27] and [28] present computer-based analyses of several polar-to-Cartesian interpolators for use in spotlight mode SAR.

(3) Publication [11] reports on results from an experimental study in constructing 2-D windows by properly contouring optimal 1-D windows. The results of this study suggest that the use of separable 2-D windows in narrow look angle SAR is near optimal, and that the special design of optimal windows for the annular sector (nearly square) in the SAR Fourier domain will lead to only incrementally improved imagery.

Extrapolation and Phase Retrieval

The main results of our research on these subjects are documented in publications [9,13]. Here the highlights are summarized. We believe that the two major reasons for the failure of existing algorithms are discretization and noise. Therefore, research has been concentrated on these issues. Some of the important results are described below.

A. Extrapolation

(1) The relationship between continuous and discrete extrapolation has been extensively studied. In particular, it was proved that under certain rather general conditions, the solution to the discrete problem converges to that of the continuous problem.

(2) It was proved that the extrapolation problem is ill-conditioned, and several regularization techniques were proposed for reducing the effect of noise.

(3) For both iterative and noniterative algorithms, we have formulated unified approaches based on Hilbert space concepts and integral equation techniques. In particular, it was shown that almost all existing extrapolation algorithms are special cases of older techniques scattered throughout the mathematics literature.

(4) We have developed two new extrapolation techniques which take advantage of a priori knowledge about the signal more readily than existing algorithms. The first algorithm uses weighted least-squares estimation. It can take advantage of the rough shape of $|F(u)|$. The second algorithm uses the concept of control points whose spacings can be varied. It takes advantage of knowledge of the approximate region within which the energy of $f(x)$ is concentrated.

B. Phase Retrieval

(1) It was proved for continuous signals that the solution to the compact-support phase retrieval problem is almost always unique in two or more dimensions.

(2) We have proven that the uniqueness property of the multi-dimensional phase retrieval problem is stable, i.e., it will not be disturbed by small perturbations of the signal f(x).

(3) We have proven that the phase retrieval problem is ill-conditioned in the sense that a small perturbation in the observed data |F(u)| may make the solution nonexistent.

Nonlinear Filtering

We have made considerable progress [10,16] regarding the development of nonlinear filters for removing noise from images while simultaneously preserving the edge structure. Some related work in edge detection has also been done. In particular, we have investigated the difficult subject of detecting edges in speckle images arising in systems such as synthetic aperture radar.

Finite Register Effects

Publications [2,4,12] detail some very useful work in finite register length effects in digital signal processing and linear time-varying filtering. This work initially started under the JSEP program, ultimately led to funding by NSF and will now be discontinued under JSEP sponsorship.

Adaptive Digital Filtering

During the last year we obtained a number of interesting results in both adaptive FIR and adaptive IIR digital filtering [1,6,8,15,19,20,21].

(1) In FIR filtering we have been studying the use of orthogonal transformations to improve convergence rates by prewhitening the input signal. In particular, it was shown that the Walsh-Hadamard transform [21] is capable of achieving improved convergence rates, similar to those known to be achieved by the FFT [1]. The Walsh-Hadamard transform is attractive for real time noise canceling filters because it involves only real arithmetic and eliminates multiplication entirely.

(2) References [15,20] present a new IIR filtering algorithm that is a modification of the "equation error" approach that has been used extensively for stochastic system identification. Global convergence of this new algorithm has been demonstrated experimentally and proved analytically. The drawback of the new algorithm is that convergence is rather slow.

(3) References [8] and [20] present a gradient algorithm, based on Widrow's LMS algorithm, for adapting an IIR filter realized with second order sections. This parallel structure is attractive because of its low coefficient sensitivity and because it is simple to monitor stability of the individual sections during the adaptive process.

This work in adaptive filtering, which was begun under the JSEP program, is now being sponsored by AT&T Information Systems, Inc. Therefore, in the future our attention, with respect to the JSEP program, will be directed toward the closely related subject of adaptive beamforming.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

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[3] M. Desai and W. K. Jenkins, "Performance evaluation and architectural implications of convolution back-projection image reconstruction for synthetic aperture radar," in *Proc. of the Int. Symp. on Circuits and Systems*, Kyoto, Japan, June 1985, pp. 1335-1338. (JSEP)

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PUBLICATIONS UNDER OTHER SPONSORSHIP:

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WORK UNIT NUMBER 26

TITLE: Basic Research in Electronics

SENIOR PRINCIPAL INVESTIGATOR:

T. N. Trick

SCIENTIFIC OBJECTIVE:

The objective of this work unit is to address fundamental problems of electronic materials, devices, and systems in a timely manner and to provide early funding on start-up projects which present immediate opportunities of high scientific merit.

SUMMARY OF RESEARCH:

During this reporting period, funds were used to support a research associate in Unit 5 and a research assistant for a new principal investigator in Unit 20. The research associate, S. A. Barnett, recently received his Ph.D. degree under the direction of Professor J. E. Greene. Dr. Barnett agreed to accept a post-doctorate position in order to maintain continuity in their research program and to complete several unfinished projects. This support resulted in the preparation of 7 journal articles and the presentation of 5 conference papers under JSEP support. Further details of this work can be found in Unit 5.

A research assistant was supported to initiate a new project under the direction of Professor Ben Wah, a new principal investigator in the computer architecture area. The research assistant has been working on the design of a VLSI high-speed floating-point multiplier which contains a recursive fraction unit.

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